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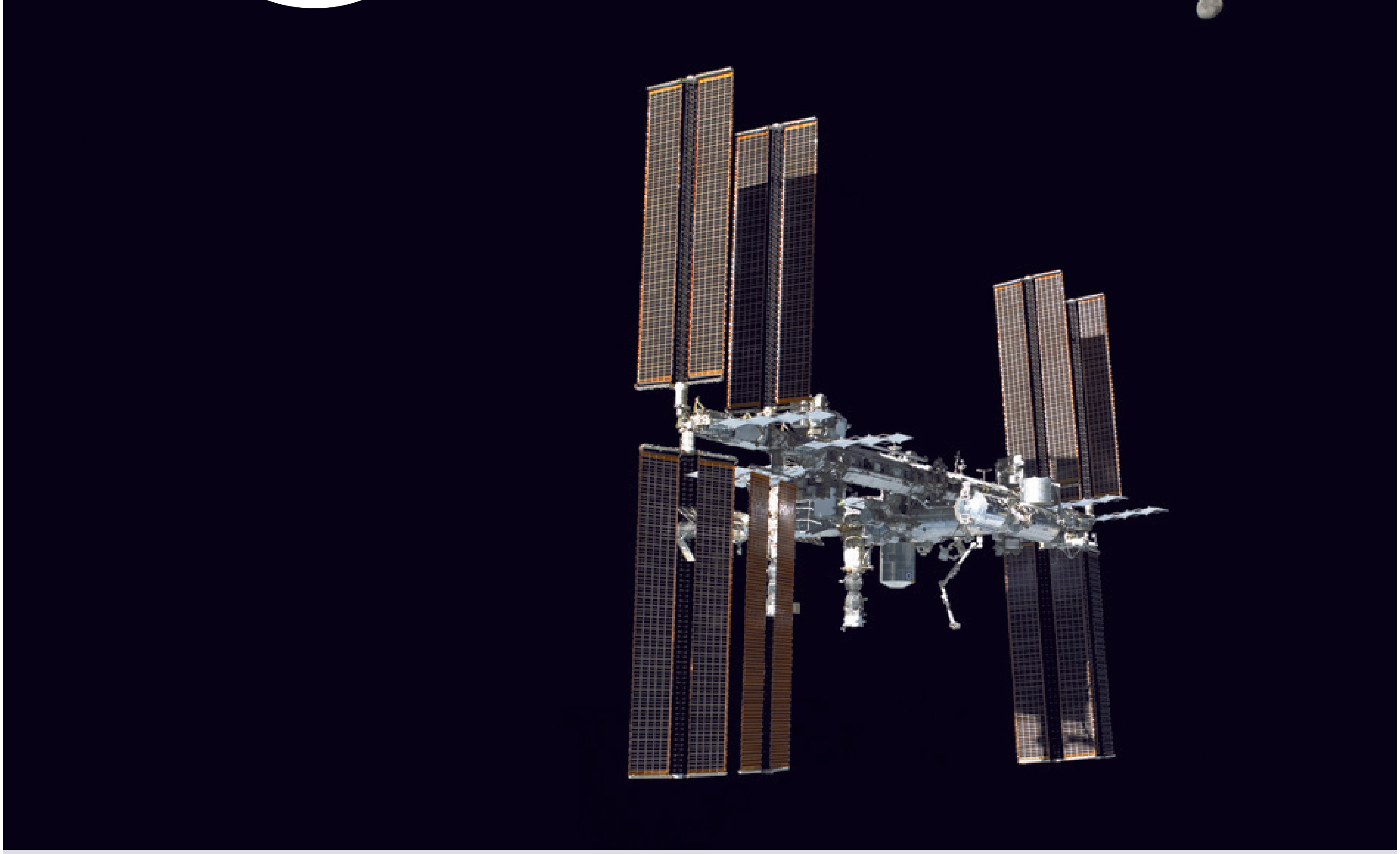

Independent Evaluation of ESA's Programme for Life and Physical Sciences in Space (ELIPS)

Final Report

European Science Foundation (ESF)

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The mission of the ESSC today is to provide an independent forum for scientists to debate space sciences issues. The ESSC is represented ex officio in all ESA's scientific advisory bodies, in ESA's High-level Science Policy Advisory Committee advising its Director General, it has members in the EC's FP7 space advisory group, and it has observer status in ESA's Ministerial Council. At the international level, ESSC maintains strong relationships with the National Research Council's (NRC) Space Studies Board in the US.
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- The European Space Sciences Committee (ESSC)
- The Nuclear Physics European Collaboration Committee (NuPECC)
- The Marine Board-ESF (MB-ESF)
- The European Polar Board (EPB)
- The Committee on Radio Astronomy Frequencies (CRAF)
- The Materials Science and Engineering Expert Committee (MatSEEC)

In the statutory review of the Expert Boards and Committees conducted in 2011, the Review Panel concluded unanimously that all Boards and Committees provide multidisciplinary scientific services in the European and in some cases global framework that are indispensable for Europe's scientific landscape, and therefore confirmed the need for their continuation.

The largely autonomous Expert Boards and Committees are vitally important to provide in-depth and focused scientific expertise, targeted scientific and policy advice, and to initiate strategic developments in areas of research, infrastructure, environment and society in Europe.

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STS-135 final flyaround of ISS 19 July 2011
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1.
Introduction and Framework of the Evaluation

In 2011, the European Space Agency (ESA) commissioned the European Science Foundation (ESF) to carry out an independent scientific evaluation of ESA's programme for life and physical sciences in space (ELIPS) and its future priorities. ELIPS is ESA's main programme for research on the International Space Station (ISS) and other microgravity platforms in various disciplines including physiology, material sciences, biology and fundamental physics. The aim of this exercise was to assess the ELIPS programme in terms of its overall structure, programmatic aspects and scientific value, and then provide recommendations for the next phase of ELIPS.

This is the fourth time ESF has evaluated the ELIPS programme; previous evaluations were performed in 2000, 2004, and 2008. This iteration, however, utilised a significantly different approach to ensure optimal results, favouring the use of a dedicated independent committee of experts rather than a broad user community consultation. This document presents the final outcome of the evaluation of the ELIPS programme over the period 2008 to 2011 and offers recommendations for its next phase.

Committee Membership

The expert committee tasked with evaluating the ELIPS programme was composed of 20 international experts in various life and physical sciences (membership list and biographies in Annex 1).

Members of the expert committee were identified by several ESF science officers holding the relevant expertise in the various fields covered by the programme, identification of experts was an independent process based on scientific merit, credentials and past experience in international committees. Careful consideration was also given to ensure that none of the committee members are currently or have been involved in ELIPS funded research projects within the past five years to prevent a potential conflict of interest in the evaluation.

Additionally, about one-third of the experts had sound experience in space research. This was an important feature of the committee composition as it allowed for external experts to analyse the ELIPS programme with a fresh, open mind, and compare it to their experiences with other non-space-related scientific research programmes.

Each of the 20 committee members represented a specific discipline that is also researched under the ELIPS programme. This allowed for the committee to give a thorough review of the quality of science being performed on various microgravity platforms in comparison to ground-based research in their field.

Framework of the Evaluation

The core of the ELIPS evaluation took place during three meetings.

Introductory meetings, 6-12 December 2011, Amsterdam, The Netherlands

During the first (one-day) meetings, representatives from ESA introduced the committee to the ELIPS programme and its main features. Presentations were given on the programme structure and implementation as well as on the four main research themes under ELIPS: physical sciences, materials science, human physiology and biology. Also, extensive question and answer sessions with the programme executives allowed the committee to gain background knowledge on the programme.

This meeting also offered the opportunity for committee members to get to know each other and to discuss and define a set of questions they wanted representatives of the programme user community to address during the 2nd meeting (10-12 January 2012).

Meeting with the user community, 10-12 January 2012, Noordwijk, The Netherlands

During the second meeting, the committee met and interacted with 24 representatives from the ELIPS user community (identified by ESA). Each represented a sub-discipline considered in the programme (see Table 1) and made a presentation following the guidelines approved in the first committee meeting (achievements, major projects, challenges of the research in their domain and list of publications). In addition to the presentation sessions (1.5 days), committee members had the opportunity to interview the users in small sub-groups for a half-day session.

LIFE SCIENCE PRESENTATIONS
Astrobiology
Behaviour and Performance
Cardio-Pulmonary Physiology and Medicine
Cell and Molecular Biology and Rodent Research
Developmental Biology
Exercise, Muscle and Bone Physiology
Gravi- and Phototaxis CES
Immunology in Space
Microbiology in Space Research
Neuro-vestibular Function
Nutrition and Metabolism
Plant Biology
Radiation Dosimetry
Radiation Risk of Space Flight
PHYSICAL SCIENCE PRESENTATIONS
Studies of Space–Atmosphere Processes on the International Space Station
Atomic Quantum Sensors and Fundamental Tests
Complex Fluids: Foams, Emulsions, and Granular Matter
Crystal Growth
Fluid Dynamics
Heat Transfer: Evaporation, Boiling and Condensation
Soft Matter: Complex Plasma, Dust Particle Physics, Colloid Physics
Close-to-Equilibrium Solidification
Solidification Far From Equilibrium
Materials Sciences: Thermophysical Properties of Fluids for Advanced Processes

Table 1: Presentations given to the expert committee on various domains under the ELIPS programme

Draft report review and writing meeting, 1-2 February 2012, Rome, Italy

The committee met a third time in Rome for two days. This working meeting was dedicated to reviewing and updating early contributions produced by the committee members as well as discussing, identifying and agreeing on overarching programmatic recommendations to be put forward in the report.

Documentation

Besides the presentations and discussion with ESA representatives and user community members, the committee based its evaluation on a set of documents made available to them. These documents included:

- Background documents (e.g. reports from past ELIPS evaluations; US National Academies – Space Studies Board Decadal Survey on Life and Physical science in Space, 2011)
- The list of experiments being implemented or waiting for implementation (on all platforms)
- Progress reports of ISS experiments that were flown over the past years with, in most cases, the list of publications produced and in some cases the publications themselves (also covering preparatory phases)
- The post-flight reports of ISS experiments completed over the past years
- The full proposals of the projects selected but not yet implemented

In addition, and following the second meeting, the expert committee requested that user community representatives provide short (about two pages) summaries on their domain before the last meeting. These were received, compiled and made available to the committee.

In order to appropriately deal with the heterogeneity of the projects presented in the physical sciences area, the committee decided to regroup some of the sub-disciplines and make some joint assessments and recommendations where applicable. As a consequence, the physical sciences section of the report has a slightly different structure than the life sciences section. However, care was taken to make sure recommendations for the future stand out clearly in both sections.

Commenting process

The draft report was forwarded to ESA's Life and Physical Sciences Working Groups (LSWG and PSWG) and subsequently presented to them at their joint meeting on 10 April 2012. A set of comments was addressed to the ESF office and then forwarded to the expert committee for its consideration.

It was felt to be very important that the (24) representatives from the ELIPS user community who presented the research activities performed in the programme also had the opportunity to comment on the draft report, especially on issues that could have resulted from a potential misunderstanding on the sub-disciplines presented or on statements that were considered to require clarification. Comments received from the user community were addressed to the expert committee for its consideration. When it was considered appropriate, the expert committee updated the report following the comments received. In some cases, and for various reasons, it was not considered appropriate to update the report following comments received. For transparency, the user community's comments that have been expressed to the committee but not integrated in the report are listed in Annex 3.

Committee Statement

The 2012 ELIPS Independent Scientific Assessment differed from previous reviews of the programme in that the panel of experts was composed of as many "external experts" as possible (i.e. persons not involved in any ELIPS research). The committee found the decision to broaden the review committee composition to be appropriate. The current model using an independent committee was deemed appropriate, and this format should be kept for future evaluations and continuously improved.

The review, however, was challenged by a tight schedule and the approach concerning documentation on the programme progress and achievements should have been better considered in the planning phases of the exercise. The presentations by ELIPS user representatives were not always optimal: in general, the committee relied on the quality of clustered project presentations from 24 selected user community representatives rather than more established and objective key performance indicators that were not available at the time of the evaluation. It has to be emphasised here that having such a wide interdisciplinary programme represented by a limited number of investigators (24) created a bottleneck in presenting the full coverage of all its disciplines and sub-disciplines. The challenges of presenting a programme of such wide, interdisciplinary character should not be underestimated, as a delicate balance must be found between overloading an external review panel with too much detail and not providing enough information. Therefore, the approach taken in subsequent reviews should evolve with the lessons learned. Likewise, evaluating such a programme is not an easy task, and the size of the committee (20) also contributed to the bottleneck. It is recommended that the expert committee composition be widened for future evaluations, to two or three external experts per discipline (similar to the ESA AO peer review process).

The metrics for evaluating research quality of the programme were not always simple to establish, in part because the acknowledgement of ESA (ELIPS) support is not always explicit. Overall, research performed in ELIPS has delivered good science, as evidenced by publication of research articles and literature surveys in high quality peer reviewed journals. However the committee noted that some user community presentations to the committee covered the full range of sub-discipline activities funded under ELIPS, whereas others ignored their brief and focused entirely on their own work. This biased tendency was also seen in the list of references supplied by each presenter.

Overall, an extended schedule, improved documentation and further interactions with the user community may enhance a future committee's ability to make as comprehensive a review of the contents, structure and impact of the ELIPS programme as desired. However, it has to be emphasised that the points addressed above only list potential improvements in the evaluation process and that the committee managed to reach a strong consensus on all the points included in this report.

The committee also observed that in most cases there is no clearly defined practice for demonstrating actions based on the previous review processes, and suggests that a formal response system be put into practice.

RECOMMENDATIONS ON THE PROCESS:

- The evaluation process would benefit from establishing a reasonable degree of continuity of "external expert" panel membership from review to review and a clearly defined follow-up process to the previous committee's work (i.e. encompassing systematic written feedback from ESA on the committee's recommendations and the way in which they are implemented or not). In addition, a checkpoint half-way through the programme could be implemented by means of a meeting of the committee to monitor developments and flag potential problems. Such a process should link with and complement existing ESA advisory structures' work and be overseen by the European Space Sciences Committee and its secretariat.
- The committee recommends that for future evaluations, clear evidence of research outputs and their impact on science/technology at large (not only related to space) should be provided to the committee and that staged peer review and refinement of AO and proposals should be considered to ensure that only the highest quality projects progress.

2.
Overarching Programmatic and Structural Issues and Recommendations

2.1 ELIPS in the Broader Scientific Landscape

The ELIPS programme is a wide ranging, comprehensive research programme providing research opportunities to scientists across Europe and beyond. It covers many scientific disciplines, spanning human physiology to fundamental physics, and utilises a variety of facilities and platforms, from rather simple equipment such as ground-based clinostats to complex ISS equipment designed and developed for specific experiments. The programme also has a variety of research opportunities, ranging from continuous calls to large-scale dedicated international research announcements. While providing many benefits, these features also make the programme difficult to approach and understand.

The expert committee wholeheartedly agrees that ELIPS hosts a number of exceptional experiments which are of top-level scientific quality and of great importance to the scientific community as well to society, and therefore should be continued.

Overall, while it is acknowledged that all implemented experiments have undergone an evaluation

Figure 1: The International Space Station provides a unique platform for long-duration microgravity studies (Credit: NASA/ESA)

process placing scientific quality as the main criterion, the quality of science under ELIPS is felt to be rather inhomogeneous. Some experiments have produced results of outstanding quality, while others failed to produce scientific results of the highest international standard.

Positioning the ELIPS programme in the broader scientific landscape is a multifaceted issue that needs to be approached from a variety of angles, as presented below.

OVERARCHING RECOMMENDATION 1:

The ELIPS programme hosts a number of exceptional experiments which are of top-level scientific quality and of great importance to the scientific community as well to society, and therefore should be continued.

Linking space research to general scientific challenges

The ELIPS programme is exploiting and providing unique conditions for investigations and research activities covering a wide range of disciplines. While some investigations performed through ELIPS are targeted towards the well-being of humans in space and enabling space exploration, the programme can also be considered as a unique and powerful vehicle to help address current scientific and societal challenges that go much beyond the programme's traditional remits. Even if sometimes representing a marginal component, the unique environmental conditions offered by the ELIPS programme can bring significant added value to scientific investigations of wider interest. This is, for example, the case in the field of metallurgy, in which microgravity conditions allow, in principle, investigation of thermo-physical properties of new alloys. Complementing other aspects of metallurgy, microgravity conditions support the optimisation of their use in industrial settings.

While it is clear that most research activities performed in the programme produce knowledge that is relevant to scientific areas going far beyond the space arena, it is felt that the ELIPS programme needs to address more of the current key scientific challenges, as recognised by the wider scientific community. In this context, some of the recommendations put forward in Part B of this report provide a first set of priority areas to be considered by ESA, but it is clear that a mechanism aimed at identifying i) key scientific challenges and ii) if and how ELIPS can support research on these should be defined and implemented.

PROGRAMMATIC RECOMMENDATION 1:

It is important to survey which current scientific challenges (going beyond the traditional coverage of ELIPS) could potentially benefit, even marginally, from the conditions and platforms offered by the programme, and to open the programme to such promising areas of research.

Reaching out to a broader scientific community

It is understood that the ELIPS programme has its own specificities that may discourage or be too complicated to assimilate for researchers new to the space arena and that medium- to long-term continuity is required to conduct complex scientific investigations. Despite the numerous specific challenges posed by space experimentation, the programme has managed to set up and maintain a stable European user community and provide opportunities to develop collaborations with scientific teams beyond Europe.

However, when considering investigators involved in ELIPS experiments and Topical Teams, the programme appears to be unable to sufficiently recruit and involve new scientists and investigators. Over the years, its user community has had a tendency to involve the same individuals and teams. Additionally (or consequently), the scientific scope of proposed and selected experiments does not appear to evolve at the same pace as Earth-based investigations. As a result, some research topics are under-represented while others are over-represented.

There is no doubt that the programme would benefit from involving new scientists in its user community. It is important to advertise the uniqueness of the programme to motivate renowned scientists to compete to perform the best possible experiments. However, even though several recommendations have been made by past ESF evaluation panels addressing the need to find ways to open the ELIPS programme to the wider scientific community, efforts undertaken thus far have not demonstrated significant improvement.

PROGRAMMATIC RECOMMENDATION 2:

To ensure quality and relevance of science performed under the ELIPS programme, ESA should investigate and implement approaches suited to widen and diversify the basis of the community of users, attracting new scientists and broadening the spectrum of experiments performed in the programme. This could be achieved, for example, through better communication to a wider community of Announcement of Opportunities (AOs) and the facilities available through the programme.

Cross-fertilisation

Cross-fertilisation among scientific topics and between teams can identify new interdisciplinary topics that should be investigated; a relevant example of such a topic relevant to life and physical sciences is the study of dynamics and rheology of blood from the scale of a single cell in the flow to hydrodynamic interactions between cells and between cells and vessel walls (e.g. the BIOMICS project).

While producing high-value, new scientific knowledge, interdisciplinary activities cannot be imposed on scientists, and targeted actions towards the development of such activities have proved to be challenging in the past. It appears that one of the best ways to catalyse the development of wide interdisciplinary investigations is to enhance the programme-wide (across life and physical sciences) interactions between science teams and the flow of information about research performed, its progress and results within the ELIPS user community itself.

PROGRAMMATIC RECOMMENDATION 3:

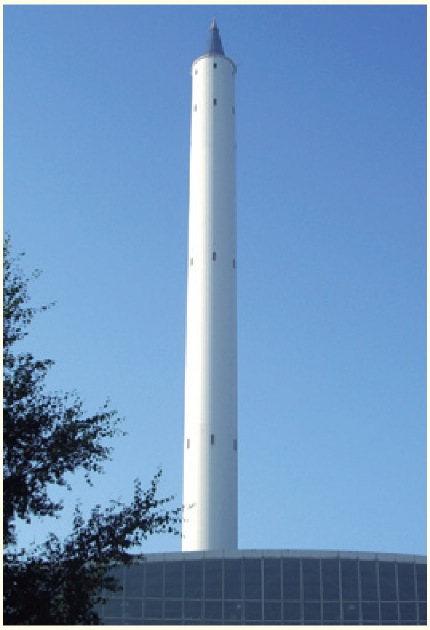
It is recommended that ESA organises regular networking events and/or user workshops involving representatives from ELIPS investigator teams from the whole spectrum of the programme. Such initiatives would provide a platform for scientists to network and discover cross-disciplinary aspects of their work, and potentially collaborate. Systematic diffusion of information about scientific publications made possible through ELIPS to the whole user community could also catalyse cross-fertilisation.

Infrastructure and facilities

The ELIPS programme offers a coherent wide variety of well-balanced platforms and equipment. Notably, ground-based facilities (GBFs) are essential with respect to preparation, optimisation and support of investigations performed in space. They allow data from one single experiment in real microgravity to be analysed in a larger context. Therefore, support of GBFs should be continued and even increased, and new mechanisms such as the development of small-scale multi-user instruments to be used in the various GBFs should be implemented.

In addition to the ISS, real microgravity conditions are currently provided by the ZARM drop tower, parabolic flights and sounding rockets through ELIPS. Given the constraints imposed by the ISS (e.g. cost, mass, power, reproducibility of experiments), the diversity of available microgravity platforms should be kept. Besides existing platforms, commercial spaceflight providers may bring new opportunities in the coming years, and the potential added-value offered by these new systems should be considered and assessed.

Current negotiations between international partners secure the utilisation of the ISS only until 2020, and thus far, no firm assumptions can be made on the fate of the central component of the ELIPS programme beyond this date. This lack of visibility beyond 2020 is viewed as a major hurdle in making the programme reach its full potential. In the current context, with less than nine secured years ahead and considering the slow pace that has been a characteristic of the programme (mostly due to resource limitations and the inherent complexity



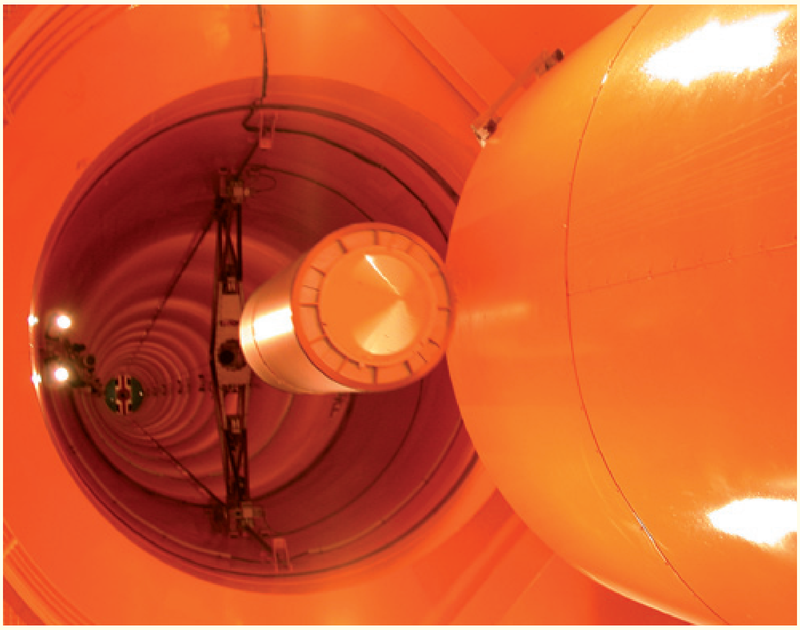


Figure 2: The Zarm drop tower in Bremen is an example of a ground-based facility that provides access to short-duration microgravity studies (Credit: Zarm/University of Bremen)

Figure 3: A view of the European Columbus laboratory module on the ISS (Credit: NASA/ESA)

of space experimentation), ambitions to perform new investigations on the ISS in the medium to long term can be hampered.

Continuous availability of long-term, man-tended in-orbit research facilities is crucial to reap the full benefits offered by spaceflight conditions for both life and physical sciences; this continuity should be ensured even after 2020. It is therefore crucial that ESA, the scientific community and the other relevant stakeholders start considering and planning the capacity and infrastructure to be made available beyond 2020 (including potential extension of the ISS utilisation). Defining the future plans as soon as possible would also allow momentum and motivation to be maintained among the scientific community and to attract new investigators.

As long as no plan is made for the post-2020 period, streamlining and shortening upcoming ISS experiments implementation phases as much as possible should be considered to optimise the use of ISS. It is also crucial to start preparing for the post-ISS period.

PROGRAMMATIC RECOMMENDATION 4:

Support of GBFs should be continued and even increased, and new mechanisms such as the development of small-scale multi-user instruments to be used in the various GBFs should be implemented.

PROGRAMMATIC RECOMMENDATION 5:

Continuous availability of long-term, man-tended in-orbit research facilities is crucial; it is therefore of utmost importance to start preparing for the post-2020 period as soon as possible.

2.2 ELIPS Programme Implementation

Coordination with national organisations

ELIPS provides a common platform for research at the European level (and beyond) and an anchor for international cooperation. One of the characteristics of the programme is that experiments are supported by several sources: ESA provides the platforms and infrastructure while all other means to conduct investigations (including sample and data analysis) have to be provided by national research organisations and this implies a double application process. Considering the number of nationalities represented in project teams, this can be (and is) a major challenge as national agencies often do not have aligned priorities or appropriate funding systems in place. In all cases, this complicates the application and reporting processes while also increasing the time that has to be devoted to paperwork.

Better integration of all the components of the research performed in the programme is required. To achieve this, coordination between ESA and national organisations must be significantly improved, and should address in particular:

1. coordinated and complementary funding of preparatory work on the ground, which is a prerequisite for successful experiments in space and
2. support for post-flight analyses of samples and data, in order to get the most out of the investments made through the experiments performed in the programme.

An appropriate mechanism to secure funding upstream in the process and limit paperwork should be set up and agreed upon between the international partners before an AO is issued. In this context, multilateral collaborative research programmes involving the setting up of (virtual) common pots of funding (e.g. the European Commission ERA-NETs+, joint programming Initiatives) could be considered as potential benchmarks.

Considering the variety of actors and partners contributing to the ELIPS programme, it seems also important that, taking into consideration national specificities (e.g. priorities, research communities), national strategies for life and physical sciences in space are developed to complement in a coherent way ESA's ELIPS programme. This would not only ease the completion of preparatory activities and exploitation of data and results but could also increase the flight options and opportunities for the community (e.g. through additional cooperative agreements).

PROGRAMMATIC RECOMMENDATION 6:

Coordination between ESA and national organisations has to be significantly improved, in particular for coordinated and complementary funding of preparatory work on the ground and post-flight analyses of samples and data. It is also crucial that research grants are secured as soon as possible in the process. Reaching a stronger integration of all the experimentations' components and setting up (virtual) common pots of funds dedicated to specific AOs could offer a way to streamline programme management while limiting the overall administrative load for the research teams (i.e. applications and paperwork).

Topical Teams

ESA Topical Teams (TT) are very valuable tools that represent the main bottom-up vector between the ELIPS programme and the scientific community. This flexible scheme allows for the coordination of experts pertaining to specific scientific issues relevant to the programme. There is no pre-detailed mandate for a TT: some are targeted towards the development of experiments to be submitted in subsequent AOs, whereas others focus on reviewing the latest developments of a field or on networking activities.

TTs play a key role in the structure of ELIPS: they are instrumental in identifying scientific issues and suitable approaches for implementation through combined ground- and space-based research platforms, they allow coordination of investigators around development and roadmapping of experimental concepts that include technology requirements and development plans and they ease the coordination of scientists who had an experiment selected in an AO. Additionally, TTs have the potential to serve as a think-tank of inspiration, giving specific knowledge and practical advice to ESA-based scientific investigations.

Currently, there are no calls for TTs nor are there priority domains advertised for TT support; one could consider introducing some degree of targeted solicitation. Rather, they can be submitted at any time and are considered for approval by the ESA's Life Sciences Working Group (LSWG) and Physical Sciences Working Group (PSWG).

As for the programme in general, TTs often involve representatives from the historic ELIPS community. As there can only be one TT per scientific topic (and some TTs have been active for more than 15 years), it may be rather challenging for individuals or groups of newcomers to join a TT and suggest and implement new approaches or concepts.

In this context, team composition is considered a crucial issue, as a TT should be the primary interface between the scientific community at large and the programme. As such, they should be responsible for attracting new scientists and diversifying the user community (this is already the case for some TTs who had their membership significantly increased – in number, scope and international coverage – over their lifetime). Rotation in their membership could be a way to address this issue. TTs should also provide a direct link to non-space research allowing the programme to be up to date with the main scientific challenges and identify important future trends and research issues. This would limit the risk that relevant areas of research possibly not covered or underrepresented in the programme are omitted.

Ideally, proposals for new TTs should be carefully reviewed by independent, ad hoc experts from the space-and non-space sciences disciplines; care should be taken to avoid the existence of vested scientific interests among the members of the user communities involved with the TT and the members of the working groups requested to assess their relevance and merit.

In order to justify continuity in the funding, progress and outcomes of TT should also be monitored and independently reviewed on a regular basis. While some TTs are aimed towards and result in an experiment proposal submitted to an ESA competitive AO (and then subject to the regular selection process), others provide reviews or foresight. The outcome of the latter should largely instruct ESA's AO process. Here again, in order to achieve this goal, the outcomes, findings and recommendations expressed by TTs should be carefully reviewed by independent, ad hoc experts.

PROGRAMMATIC RECOMMENDATION 7:

Because of its strategic importance and the improved quality it has brought to the programme, the TT scheme should be continued. However, the rather loose selection and implementation procedures do not seem to reflect the importance the TT concept has for the programme. Therefore, the whole TT scheme should be reviewed in detail and restructured. Specifically, issues such as the following should be considered:

- **Advertisement of TT opportunities**
- **Selection process**
- **Team composition and how to involve newcomers and early career scientists**
- **Rotation of the coordinator**
- **Regular review and rotation of TT membership**

Mixing directed research with curiosity-driven activities

In its implementation, ELIPS encourages scientific curiosity and blue sky research. As previously mentioned, it is also important that the research performed in ELIPS contributes to addressing major scientific challenges and the most compelling questions of wide interest and potential impact. Furthermore, the programme would also benefit from addressing space-specific issues (e.g. in the field of space exploration) of high relevance. While the current open-ended research solicitation process does not prevent such activities from being proposed and performed, it is clear that it does not motivate pre-defined key issues to be put forward and/or be investigated within ELIPS. It is felt that some targeted calls addressing specific priority research topics could complement the current curiosity-driven process.

This could be implemented by reconsidering how AOs are structured and implemented, and defining and designing rather detailed research plans complementing open-ended solicitations. In this regard, and through an analogy to calls of the EU Framework Programme (FP) and the European Research Council (ERC), one could envisage more topic-oriented AOs reflecting some of the principles of the EU FP "collaborative projects". These could then be mixed or alternated with open-topic calls,

Figure 4: The ELIPS programme frequently utilises Zero-G flights as a microgravity platform (Credits: Zero-G/ESA)

similar to those supported by the ERC. As a consequence, some of the research performed by ELIPS could be targeted towards topics of high strategic relevance as defined suggested by ESA and agreed by the programme board.

PROGRAMMATIC RECOMMENDATION 8:
Overall, the programme should be more able to address targeted scientific priority topics. Some degree of targeted research should be introduced to mobilise some of the investigations performed towards topics of strategic relevance. This should be based on the inputs and recommendations originating from various sources (e.g. ESF, Topical Teams or ESA's Working Groups). ESA should investigate ways to mix targeted activities with curiosity-driven research.

Announcement and selection of experiments

The ELIPS programme involves various research solicitation approaches: experiments involving simple ground-based facilities (e.g. drop tower or bed-rest) can be submitted at any time through Continuous Research Announcements (CORA), experiments involving more complex ground-based facilities (e.g. Concordia Antarctic station or the GSI Accelerator Facility) can be submitted via dedicated AOs approximately every two years. Experiments involving space-borne facilities (including sounding rockets) are subject to calls that may involve international partners with a common peer review process. Over the past 12 years, these major calls are typically issued up to once every four years, depending on the discipline.

For each type of call, experiment proposals are first evaluated on scientific merit by external peers (from a mail-refereeing process for CORA to the setting up of review panels with physical meetings in the case of dedicated AOs). All experiments recommended for implementation following the scientific review phase then undergo a technical feasibility evaluation that may disqualify some experiments from implementation (due to issues like upload capacity, availability and reliability of technologies or in-orbit resource requirements). Experiments that pass the selection process successfully are then integrated with the ELIPS pool of experiments until actual implementation – for technical or programmatic reasons – is made possible. Some experiments can be, and have been, waiting in the pool for several years. ESA advisory committees re-assess the relevance of the projects sitting in the pool for more than three years, calling external peers if considered necessary.

Considering the long time between major AOs (in the range of four years), the review process should allow the proposing teams to comment on the early review reports made by peers before review panels actually meet and finalise the evaluations. This would allow clarification of potential misunderstanding from some peers and possibly resolve some issues without waiting an additional four years.

The fact that experiments selected to fly sometimes await implementation for several years is seen as a major issue not only for the ELIPS user community, but also for the committee (see below: turnaround time). In addition to proper evaluation and selection processes to ensure the quality of the programme, ESA should also manage the pool of experiments waiting to be implemented in an appropriate manner. In this context, it is crucial that experiments that have been waiting for a long period of time to be implemented should be re-evaluated, especially with regard to relevance, through a review process of the same standards as in the selection process. Such an approach could be systematically adopted just before entering phase B (definition phase, when the baseline technical solution and technical requirements are defined) of any research project that has been waiting implementation for more than three years.

PROGRAMMATIC RECOMMENDATION 9:
There is a need to further ameliorate the review process implemented in ELIPS. Implementing a rebuttal step in dedicated AOs would definitely improve the selection process.

PROGRAMMATIC RECOMMENDATION 10:
Experiments awaiting implementation for more than three years should be systematically re-evaluated before entering phase B. The same standards and process implemented for the original evaluation and selection of experiments should be used for this re-validation step.

Increasing the scientific outcome of the programme

The ELIPS programme offers unique conditions and therefore provides opportunities to perform exceptional experiments of top-level scientific quality and of great importance to the scientific community. However, a major drawback of the programme is that it provides the opportunity to experiment only on small samples and on a small number of subjects (e.g. for human physiology), and often experiments cannot be reproduced. As a result, the data produced can be limited, preventing investigators from publishing in high impact peer-reviewed journals. While increasing the opportunities to complement flight experiments with ground-based experiment provides an opportunity to partly overcome this problem, an optimal balance must be found between quantity and quality of the science that is performed. Sufficient resources should be allocated to allow the comprehensive study of high priority questions or experiments of outstanding quality. Therefore, ESA should consider selecting fewer experiments and allocating more resources to each of those selected.

In addition to being more selective on experimental proposals, improving the automation of equipment and instruments and, where appropriate, the ability to operate them remotely would decrease the need for crew time, a valuable resource.

PROGRAMMATIC RECOMMENDATION 11:
The success of the programme should be quantified by its ability to efficiently answer specific questions in a comprehensive manner. The number of experiments implemented is not considered to be a valuable quality control indicator. Therefore, and when relevant, ESA should consider increasing the level of resources allocated to experiments to strengthen their case and the validity of their results even if this implies implementing fewer experiments.

Turnaround time

In most cases, the time from the AO to actual implementation of an experiment on the ISS exceeds between three and five years – even for simple experiments – and can exceed ten years. This excessive delay is seen as a major issue (by the committee but also the user community) that has to be improved in the programme. The long implementation time has several consequences:

- at this rate, only a small fraction of experimenters would feel motivated to propose and develop an experiment, thus reducing the community of potential users,
- considering changes of staff in research teams (including retirement) and organisation in research institutes, the loss or discontinuity in knowledge and competencies can be very significant from the moment an experiment is submitted to the time it is actually implemented,
- more important is the crucial issue of ensuring that an experiment is still scientifically relevant at the moment it is finally implemented.

It is acknowledged that this very long turnaround time is partly due to events that have had major impacts on the programme implementation: some experiments were lost during the Foton M1 failure (15 October 2002) and the STS 107 catastrophe (1 February 2003) and had to be re-flown. Furthermore, following the Columbia accident only one shuttle mission was flown over three-and-a-half years, making obsolete all previous plans concerning ISS assembly and crew size, as well as upload and download capacity.

Time between selection and actual experimentation depends on programme implementation aspects (e.g. flight sequence, upload mass capacity) but also on the hardware development process (if required). This greatly depends on the complexity of the equipment to be developed and the relation with the industrial teams.

By nature, some experiments are more complex and require a long implementation period, but others use existing hardware (e.g. KUBIK) and therefore can be implemented much more rapidly. ESA should consider issuing AOs that are specifically targeted to existing equipment or processes that would allow a fast track implementation. For other longer term AOs, the long implementation time has to be made clear as soon as possible in order to avoid frustration.

Efficient practices have been developed by some countries or research teams, including some nationally supported Soyuz taxi flights that allowed experiments to be implemented rather quickly, or having the research team build (as a sub-contractor) the science part of an experimental set-up, reducing hardware development time. These are only examples of potential opportunities among others that need to be identified. To this end, audits should be conducted by external auditors able to cast a discerning eye on the processes and procedures of programme management and hardware development, and to identify the best practices and suggest recommendations for improvements.

PROGRAMMATIC RECOMMENDATION 12:
ESA should consider implementing fast-track AOs, e.g. dedicated to existing hardware (for example, Kubik) and allowing rapid implementation. Such AOs could be issued every two years.

PROGRAMMATIC RECOMMENDATION 13:
ESA should find a way to identify and list the most efficient practices in terms of programme management (e.g. national Soyuz taxi flights) and development (e.g. involving the scientific team as a subcontractor). This could be made possible via an external audit performed by a contractor.

Reporting and data archiving

Through the ELIPS programme, ESA provides in-kind support to research projects: facilities, equipment and logistical support required to perform a given experiment. While this represents a significant investment from the agency (285M€/4years), ESA does not actually grant funding to the selected teams. Ground-based preparatory activities, exploitation of data and workforce must be funded by other means, usually through participating Member State research organisations. ESA has some clear reporting guidelines for scientists but does not have efficient compulsory means to enforce them, and investigators tend to report solely to their national sponsors. As a result, it appears as though the programme does not systematically have feedback on the outcomes of performed experiments. Furthermore, it appears that publications produced through an experiment implemented within ELIPS often do not acknowledge the programme or even ESA. As a result, reporting on the programme value and success is a challenging task for the programme executives.

Scientific reports should be provided in a one-to-one correspondence that includes projects' aims and milestones. Publication records should be constantly updated and limited to the work directly supported – and for which proper acknowledgement is mentioned – by ESA and the national research organisations. The issue here is not that reporting information is not available at all, but rather that it is submitted on a regular basis sometimes exclusively to national research institutions. Even though it has proved challenging to impose a systematic reporting process to investigators directly, ESA should explore ways to improve the flow of information with national research organisations.

Proper reporting would not only allow the value of the programme to be assessed and demonstrated, but it should also allow improvement of the level of information made available to the community at large. The online EEA (Erasmus Experiment Archive) is a very valuable tool, but it is obvious that research teams do not provide the same level of detail when compiling their information. EEA needs to become a reliable, updated and user-friendly database of research products. This is of paramount importance not only for the proper exploitation of such products and to avoid duplication, but also for the evaluation process.

PROGRAMMATIC RECOMMENDATION 14:
ESA should investigate and implement new strategies to improve the flow of information back to ESA after the experiment has been implemented. This includes acknowledgement of the ELIPS programme, results from experiments, and publications and could involve specific agreements with national research organisations.

PROGRAMMATIC RECOMMENDATION 15:
ESA needs to investigate ways to make the Erasmus Experiment Archive a more reliable, updated and user-friendly database of research findings made possible by the ELIPS programme, for the proper exploitation of such knowledge by the scientific community at large.

Figure 5: An astronaut working outside the ISS (Credit: NASA)

3.
Life Sciences

3.1 Overarching Issues and Recommendations for the Life Sciences Programme

Space provides a unique opportunity to advance the fundamental understanding of living systems by performing experiments in microgravity. These experiments not only benefit astronauts, but are vital for future human exploration of space, and also have the potential to bring wider benefits to human health and society, for example through improved healthcare.

A detailed review of life science research under the ELIPS programme was performed, and specific evaluations/recommendations were provided for each sub-discipline. From these analyses, several overarching issues and recommendations emerged during the review process. Those that cut across the whole life science area fall under two main topics: promoting cutting edge science and cross-disciplinary interactions and integrated physiology.

Promoting cutting edge science and cross-disciplinary interactions in life sciences

The revolution over the last 20 years in understanding life sciences at the molecular level has resulted in a host of new techniques and instrumentation for characterising biological systems that are capable of producing large amounts of data systematically. The ELIPS programme has lagged behind the cutting edge of this revolution, partly due to the time lag in developing and uploading needed instrumentation to the ISS. In the light of this, the following recommendations can be made:

OVERARCHING LIFE SCIENCES RECOMMENDATION 1:
Identify and implement mechanisms to ensure faster deployment and use of new investigation techniques and technologies in the programme.

OVERARCHING LIFE SCIENCES RECOMMENDATION 2:
Implement mechanisms to promote interdisciplinary interactions within the Life Science programme to i) learn from common experiences, ii) enhance the use of existing facilities and iii) develop more shared instrumentation.

OVERARCHING LIFE SCIENCES RECOMMENDATION 3:
Promote interaction between sub-disciplines such as immunology, radiation biology, microbiology, cell and molecular biology and nutrition, and encourage trans-disciplinary projects, such as integrative physiology, that couple quantitative modelling with experimental work.

OVERARCHING LIFE SCIENCES RECOMMENDATION 4:
Encourage projects that examine the interactions between the living organisms' genome and environmental factors including microgravity, radiation, desiccation, etc.

OVERARCHING LIFE SCIENCES RECOMMENDATION 5:
Refine AOs so that in addition to the provision of projects to test a hypothesis by collecting specific data (hypothesis-driven research), it is possible to propose projects where the emphasis is on collecting large datasets for subsequent analysis and data mining (data-driven research).

OVERARCHING LIFE SCIENCES RECOMMENDATION 6:
Implement a strategy for data sharing, so that communities beyond the current reach of the ELIPS programme can benefit from experiments that have already been carried out.

Integrated physiology

Ground-based research (GBR) focused on the understanding of the mechanisms of ageing and the impact of sedentary life style, diet, ionising radiations and gene expression is critical for developing new strategies to promote health and for discovering new treatments of diseases.

Microgravity-related research offers unique opportunities to test and verify results obtained by GBR within a reduced time frame (e.g. impact on bone health) in order to evaluate the efficiency of new countermeasures for ground medicine (e.g. prevention of sarcopenia), as well as to acquire the needed knowledge to allow for space exploration by humans.

Understanding how the human body responds to microgravity has been a long standing pillar of space science research because of the practical importance for the health and well-being of astronauts. Within this specific part of the life sciences remit, crew time is a significant constraint on research activities that can be performed on the ISS. One way to overcome this would be to manage/steer the research programme so that the use of animal models is maximised and that a smaller number of projects are selected so that crew time can be optimised.

Specific recommendations for the aspects of the ELIPS Life Sciences programme related to human physiology include the following.

OVERARCHING LIFE SCIENCES RECOMMENDATION 7:

Promote and facilitate the integration of (human) physiology sub-disciplines.

OVERARCHING LIFE SCIENCES RECOMMENDATION 8:

Further address the links between physiology, psychological performance, and human-computer interactions, which have been overlooked up to now.

OVERARCHING LIFE SCIENCES RECOMMENDATION 9:

Increase the capacity to perform research on animal (rodents).

OVERARCHING LIFE SCIENCES RECOMMENDATION 10:

Design and refine cell and animal models specifically suited to address mechanistic issues related to environmental stressors typical of space-flown missions.

3.2 Human Factors and Physiology

3.2.1 Behaviour and performance

Introduction

Astronauts in long-duration space missions will encounter some major challenges; they will need to acquire and maintain operational skills and competencies under microgravity, perform in teams during prolonged confinement, and work under continuous stress caused by danger and the threat of unexpected and unknown encounters. The relevance of such concerns for space missions has long been recognised, and research on psychology-related problems will continue to have a major significance as long as human crews are part of future plans for space exploration. Part of the rationale for this is the belief that humans have often been perceived as the 'weak link' in the system, though this is an over-simplification; as with all complex human–machine systems, the origin of the weak link is better regarded as the interaction of humans with the design of their working and operational environments. It is necessary to recognise two broad objectives of studying astronauts' behaviour in space. One is the need to assure successful and safe fulfilment of mission goals; the other is to understand how existing (Earth-acquired) competencies and skills can be adapted for effective operation under microgravity. Since it is unlikely that fully automated missions can deliver the necessary flexibility and problem-solving capability required by extended missions, research will need to focus on problems related to the vulnerability of crews to the demands of the space environment, and how systems can be designed to support their activities. Issues such as the limits of human skill maintenance, the reliability of performance under stress, health and well-being, and crew interaction processes remain central to the ELIPS programme.

Space relevance and value of ELIPS programme to behaviour and performance research

Research on space-related problems does not always fully address its significance, for either the space environment or Earth-based issues. The unique issues posed by living and working in space mean that such research (especially where access to ISS is required) should be able to demonstrate its relevance to the distinctive problems associated with microgravity, stress (danger and threat, radiation, etc.) and extreme isolation and confinement environments (ICE). However, much of the work currently being funded under ELIPS does not meet these criteria. Instead, as with most psychology research on space issues, its rationale depends on established ground-based ICE simulations, such as Concordia *(Figure 6)* or Mars 500.

Figure 6: The Concordia Station is a scientific base built in Antarctica by the French Polar Institute (IPEV) and the Italian Antarctic Programme (PNRA) (Credit: IPEV)

Due to the long duration of ISS missions and the space environment, it is a highly appropriate research platform for the investigation of some topics (for example, the consequences of microgravity for existing skills and acquisition of new ones, and effects of extreme stress on skill and performance), while others (group processes, social interaction) may often be investigated equally well in ground simulations. Most of the funded work falls into this second category; although it is appropriately couched in terms of space problems, it addresses issues that are standard features of Earth-based research in similar areas. Some aspects of work on group processes could justify inclusion as part of an ISS programme, for example by making use of the increased stress and threat of that environment, though it would be necessary for social interaction measures to be combined with performance assessment. It should also be said that research on group processes are particularly susceptible to the persisting methodological problem of limited sample size characteristic of ICE simulations, making it necessary to collect data from multiple replications in order to build up large enough group sizes for reliable analysis. However, this is not normally possible within the constraints of the programme, making the value of such studies with ELIPS questionable. Some social interaction studies clearly have a value in terms of their application to Earth-based issues, though they may be better conducted as part of Earth-based research.

Assessment of past period

Assessing the research performed on behaviour and performance under the ELIPS programme was difficult due to the lack of relevant information. In particular, the committee did not have access to a list of relevant publications from ELIPS-supported projects, so was unable to establish exactly what work had been done. Some references were provided by a presentation on the topic and in a summary document, but most of these were only from two researchers. As a result, much of this evaluation had to be based on approved proposals to be implemented rather than research outputs. Another constraint is that many current projects were carried out under the Mars 500 and Concordia 2010 programmes, and are not yet completed or available in any accessible form.

Given the sparse and indirect nature of available information, a detailed assessment has not been possible. However, some clear issues emerged. First, the scope of the work supported by ELIPS appears to be quite narrow, mainly concerning traditional issues relating to the social psychology of groups and psychological health and well-being. Despite the name of the sub-theme, little research effort has been devoted to the more technical areas of skilled performance, training and cognitive behaviour. Second, the goals of the research, with some exceptions, are quite modest. While most of the work is competent and well conducted, significant achievements are not apparent. This criticism applies especially to projects that are wholly psychological in nature, with little evidence of advances in fundamental understanding. For example, the summary document reports that crew functioning was effective under increased autonomy, but this conclusion comes from questionnaire data only, whereas performance data are essential (and more fundamental) for demonstrating such a finding. This applies also to the statement in the summary that the crew got lonely during the long period away from family and friends during Mars 500. Loneliness is certainly expected to be a problem during long missions, and may affect the performance of individual crew members. However, the observation of loneliness by itself is not that useful; what is needed is evidence for the ways in which such effects may occur. Some other projects are more promising, mainly involving links of psychology with issues such as exercise physiology and cardiovascular functioning, though these were not covered by the summary document or presentation.

The general inference is that there may be a level of conservatism in the methods used for project selection, whereby the programme attracts applications from the same small pool of researchers. The absence of any clear priority-driven direction has allowed the area to become dominated by familiar themes and research groups. Much of the current research activity looks very similar to the extensive body of work carried out during the 1990s. It is no longer at the cutting edge of the discipline, let alone representative of the broader range of major research questions.

FUTURE PRIORITIES AND RECOMMENDATIONS

BEHAVIOUR AND PERFORMANCE RECOMMENDATION 1:

A marked shift of focus should be implemented, particularly where access to the ISS platform is envisaged as a realistic goal for projects in behaviour and performance. In particular, some top-down guidance is required, promoting the need to address important topics that have been neglected: skill and performance maintenance; monitoring and support for crewmembers under stress; problems of interaction of crew with complex equipment and automation.

BEHAVIOUR AND PERFORMANCE RECOMMENDATION 2:

There is a need to study crews as teams of operators who carry out mission-related tasks, including a concern with the dynamics of crew cognition and skill flexibility, rather than only in terms of group interaction processes. An important core requirement is the need to develop and implement an integrated monitoring capability for individual crew members, including not only behavioural and interpersonal measures, but on-going physiological state. In this context it is important to create a strong link between psychological questions and those addressed by neuroscience and by cardiovascular and exercise physiology, in the search for underlying compensatory mechanisms and common patterns of adaptation to microgravity.

BEHAVIOUR AND PERFORMANCE RECOMMENDATION 3:

As to methodology, all the suggested new directions depend on being able to study effects of the space environment on 'steady state' behaviour on the ISS or in ground simulation conditions (i.e. well-learned tasks with no further improvement occurring during the testing phase, making changes impossible to interpret). This has been a major problem in most previous research on performance, and undermines even the best research plans. It can only be overcome by ensuring that adequate provision of time and opportunity for training, prior to starting testing, is formally built in to the human testing schedules.

3.2.2 Exercise, muscle/bone

Introduction

Adaptation of the human musculoskeletal system to spaceflight includes 1) increased renal excretion of calcium, as well as a potential reduction in enteral calcium absorption, 2) enhanced bone turnover and bone loss at locations experiencing greatest reductions in strain, 3) reduced bone formation and oestrogenic differentiation of mesenchymal precursors, and 4) a regional change in lean body mass with significant losses of muscle mass and strength at the lower extremities, mirroring those of bone and enhanced by the confined-environment-related hypokinesia during flights. All of these changes may produce harmful effects during long-duration spaceflight by exposing crew members to skeletal fractures and risk of renal stones. The changes to bone turnover are largely reversible; however, there is a possibility of irreversible effects of altered bone cell functions, which may lead to a risk of premature osteoporosis, especially for those undergoing multiple missions with hypokinesia and microgravity. The interrelated dysfunction of bone and muscle tissue homeostasis in microgravity might also carry additional health risks, since both muscle and bone are capable of expressing and secreting factors that impact on pancreatic insulin secretion, fat cell accumulation and maturation, phosphate metabolism and vessel wall cell differentiation.

Space relevance and value of ELIPS programme

As exercise and muscle bone metabolism are related to the human ageing process, research in this area is highly relevant to the physically inactive senile population. Comparison between altered bone and muscle cell function by microgravity and bone and muscle atrophy on Earth should provide important insights into the pathogenetic factors involved, enabling targeted interventions for the treatment of osteoporosis, sarcopenia and falling risk, which are major causes of disability in the elderly population. Long-duration spaceflight might also give insight into the mechanisms of ageing. The underlying molecular pathways might be different, but the characterisation of spaceflight-related effects on physiological function could enhance our understanding of the human lifespan. Similarities also occur between microgravity and spinal cord injury (SCI), since both are associated with deterioration of physiological function, not only in bone and muscle, but also in the cardiovascular system and immune response. Exploring the effect of reduced gravitational forces will therefore provide important insights for the development of effective strategies against SCI-related negative outcomes.

Assessment of past period

Projects funded under the ELIPS programme were mainly based on the assumption that the mechanical environment dominates bone and muscle mass plasticity for a given gene network. The projects were aimed to characterise bone and muscle responses to spaceflight, and to counteract the deleterious effect of prolonged gravity-unloading by physical exercise (either resistive, vibration, endurance or a combination). Experimental settings have included crew members or animal models in space, flight analogues including tail-suspended rats on the ground, and human subjects at head-down bed rest (HDBR) *(Figure 7)* and at reambulation.

Figure 7: In bed rest studies, candidates lay in bed for extended durations of time, with the head tilted down six degrees (Credit: ESA)

Major achievements in the last five years have provided important information on bone and muscle wasting processes outlined above, confirming that flight analogues can mimic some but not all aspects of the space environment, and that physical exercise can counteract muscle atrophy and bone loss in the ground-based microgravity analogue of HDBR. Standardisation of the procedures in bed rest studies, as recently achieved, should also be regarded as a progress, allowing the creation of systematic databases. The ELIPS programme has driven research on the effects of microgravity and simulated microgravity on bone and muscle cells and how the resulting changes can have systemic consequences. The mechanotransduction process that translates mechanical forces into signalling pathways that dictate adaptive cell responses has been further dissected, since this mechanism is pivotal in understanding the adaptation of bone to mechanical loading.

RECOMMENDATIONS

EXERCISE, MUSCLE AND BONE RECOMMENDATION 1:
The mechanisms of adaptation to microgravity and response to exercise in a specific subject are not well characterised. Future studies should be directed towards dissecting the components of structural adaptation related to muscle-derived and gravity-derived loading. Exercise programmes should also be designed to avoid post-loading bone desensitising processes, and be modelled following a more mechanistic and hypothesis-driven approach, based upon recent knowledge on related domains.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 2:
The design and consideration of ground-based analogues are mainly restricted to the two models outlined above, i.e. HDBR and tail suspension, but other experimental and clinical models such as Ko mice with targeted modification of the bone and muscle adaptive responses and spinal cord injury should be considered.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 3:
Whereas the variability in spaceflight- and space-analogue-related bone loss and muscle atrophy have been consistently acknowledged, the factors that influence individual rates of post-flight recovery, and in some individuals the lack of recovery, are still unknown despite more than 20 years of space flights and bed rest studies. These factors should be further investigated.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 4:
Gold standards for human-based exercise experiments should be enforced within the ELIPS programme. As recently outlined for animal-based exercise studies, exercise responses and adaptations should be reported using standardised means to ensure reliable data, appropriate interpretation and comparisons.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 5:
The efficiency of vibration exercise in counteracting bone and muscle wasting during space flight and flight analogue studies is still under experimental scrutiny, in particular because of its potential anabolic effect on bone. Despite its wide use in the ELIPS programme, there are

knowledge gaps that should be covered including the mechanism of action and clinical effects, and the heterogeneity of the protocols used. It is also argued that "vibration only" would be of limited value in counteracting muscle atrophy during long duration space flights and HDBR, although a bone effect is feasible.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 6:

The potential dysfunction under microgravity of muscle–bone cross-talk by the alterations of its paracrine, autocrine and endocrine constitutive factors, and the modulatory role of its operational state by the neuronal system have not yet been explored under the ELIPS programme. However, the muscle–bone interface is of current interest for the understanding of bone and muscle metabolism, and a focus on this topic might provide new insights into the functional and developmental interaction between muscle and bone.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 7:

Extending studies to include nutrition–muscle–bone interactions would be challenging in view of the interdisciplinary effort required, but a systematic approach to assess the functional state of the bone–muscle cross-talk system under specific physical exercise and nutrition regimens would enable a wider perspective of the bone and muscle adaptive responses.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 8:

Human primary osteocyte models should be further developed, as they are the master bone cells constituting a matrix-integrated functional syncitium with a plethora of functions involving the control of bone remodelling, contribution to short- and long-term error correction mechanisms in acid–base equilibrium and plasma calcium homeostasis, mechanotransduction processes, microdamage repair, oxygen sensing, vascular control, and production of factors and regulators of mineral and possibly muscle metabolism. Since osteocytes are embedded throughout the mineralised matrix, they present major challenges due to their difficult accessibility and the few models available in vitro displaying all their functions. 3D culture models of bone cells are going to be developed (MEDES–ERISTO programme) on the assumption that primary human osteoblasts can be induced to differentiate into osteocytes in 3D scaffolds. These models should be further implemented since bone remodelling functions require complex 3D arrangement to be fully exploited. Projects in this direction have already been funded by ESA and are essential for adequate investigation of osteocyte metabolism in microgravity.

3.2.3 Cardiovascular and pulmonary systems

Introduction

Gravity and posture both have a profound impact on the distribution of fluid within the human body, and thus are important for the function of the human cardiovascular and cardiopulmonary systems. The heart must generate sufficient pressure to ensure blood flow to the brain while standing and lying down, and similarly, the lungs must adapt to maintain both ventilation and perfusion. Although well characterised in general, gaps remain in the knowledge and understanding of how these systems behave, particularly in disease states. For example, mechanisms of conditions such as vasovagal syncope (a failure of the system that regulates blood pressure) are not well characterised or understood. Experiments in microgravity provide a way to address some of these gaps.

Space relevance and value of ELIPS programme

A detailed understanding of how the human cardiopulmonary system responds to microgravity is essential for ensuring the health of astronauts during long-duration space flight, and so is highly relevant to human activity in space.

As well as the benefits for human spaceflight, there are also basic scientific insights from the ELIPS programme that are relevant for understanding terrestrial human physiology and pathophysiology. A specific example includes the fundamental understanding of how set points are established for the human blood pressure control system, and how these set points enable the cardiovascular system to respond rapidly to changes in posture.

This activity is relevant to terrestrial physiology because insights into fundamental physiology can enable the development of new interventions for patients. For example, a more detailed understanding of airway inflammation in microgravity resulting from exposure to dust would be expected to result in new ideas for treatment of common conditions such as asthma.

There is also relevance to other areas such as exercise physiology, which is also important for spaceflight.

Assessment of past period

Assessment of ELIPS projects in the past period was based on the report and presentation made to the committee.

In parabolic flight, microgravity has been found to have immediate effects, including an increase in cardiac output and decrease in systemic vascular resistance. For longer duration (several days or more) spaceflight, there are longer term effects of blunting the baroreflex, which alters the control of blood pressure and heart rate, and in some astronauts this results in poor regulation upon return to Earth. These findings have also established that the set points for cardiac output and systemic vascular resistance in microgravity are mid-way between the values for lying and seated in normal gravity.

The effect of microgravity on the lungs is rather more subtle. Although there are likely to be some small effects on lung mechanics and the configuration and resistance of the pulmonary circulation, the focus of recent work *(Figure 8)* has been on the production of nitrogen oxide (•NO). •NO production can be used as a non-invasive marker of airway inflammation, but is also influenced by the distribution of blood flow within the lung. Studies in the past period have shown a fall in •NO production in prolonged microgravity, which is consistent with an increase seen in hyper-gravity, and with a dependence of •NO production on blood flow distribution in the pulmonary circulation. These findings are important for interpreting measurements of •NO production, and so can be used for monitoring the long-term exposure of astronauts to potentially toxic dust.

In the past period, good use has been made of parabolic flight and bed rest to complement spaceflight experiments. Research outputs from groups funded under this programme tend to be in (not space-specific) physiology journals rather than space science journals, and have a good number of citations.

Figure 8: In an experiment on the ISS, exhaled NO was measured (and was found to be greatly reduced in microgravity) (Credit: ESA)

FUTURE PRIORITIES AND RECOMMENDATIONS

CARDIOVASCULAR AND PULMONARY SYSTEMS RECOMMENDATION 1:

The two main bottlenecks for experiments involving cardiopulmonary physiology are instrumentation and crew time. Experimental work in prolonged microgravity is constrained because of restrictions on upload that prevent the use of detailed imaging modalities such as MRI. Recent projects have addressed to some extent the problem of developing lightweight instrumentation (e.g. ambulatory blood pressure monitoring), and there is scope for more innovation in this area combined with the instrumentation available on the ISS European Physiology Module. These aspects should be further addressed in the future. The deployment of ambulatory instrumentation also helps to minimise the constraint of available crew time because experimental work can be combined with other crew activities.

CARDIOVASCULAR AND PULMONARY SYSTEMS RECOMMENDATION 2:

There are clear links between the effects of spaceflight on the cardiovascular and pulmonary systems, and the effects on the musculoskeletal system and the response to exercise. Opportunities to bridge these disciplines should be sought.

CARDIOVASCULAR AND PULMONARY SYSTEMS RECOMMENDATION 3:

At present data collected under the ELIPS programme are not always available within the wider scientific community. Research in this area could be stimulated by making these data more widely available, perhaps through a portal similar to the online PhysioBank facility (http:/ www.physionet.org/physiobank/). Effective data sharing would open up the recordings from previous projects to other communities including physiological modelling. Integrative models of human physiology are becoming widely used research tools because predictive models enable hypotheses to be both tested and generated. This approach can complement microgravity experiments because in a model, gravity is a parameter and can be switched off. Data sharing would enable this type of model to be parameterised and evaluated using recordings from human spaceflight or parabolic flight.

3.2.4 **Neuro-vestibular**

General statement

Gravity provides a continuous reference direction for the organisation and coordination of all sensory and motor systems on Earth. Consequently, its absence not only affects the function of the primary sensory system involved in gravity perception, the vestibular system in the inner ear, but also multisensory perception and motor action in general. Thus, research in this field includes questions such as how the central nervous system compensates for the absence of gravity by reconstructing references from other sensory modalities, how limb coordination for reaching and grasping is affected, how optimisation of motor commands is modified, and how visual perception of an object's properties such as its distance or size depend on gravity *(Figure 9)*. Since vestibular input has a critical influence on brain structures such as the hippocampus, it is conceivable that memory and cognitive function are also affected by a lack of gravity. The research methods used range from neurophysiology, both in animal models and in human subjects, to behavioural investigations and mathematical/computational modelling.

Space relevance and value of the ELIPS programme

Microgravity, i.e. the absence of gravity, provides a unique opportunity to study aspects of multisensory integration and motor coordination in the absence of the dominant sensory cue determining the spatial reference direction of up–down. As such, studies in microgravity can give critical experimental evidence for pertinent questions in the investigation of sensorimotor and cognitive function and for the validation or rejection of hypotheses and models. The past period has seen a couple of excellent examples utilising this approach.

Successful manned spaceflight requires a good understanding of sensorimotor and central nervous function in microgravity. As such, the present topic clearly has the potential to be applied in planning future space flights. As an example, investigation of the effects of artificial gravity by centrifugation on sensorimotor function could be useful for long-term missions. Other applications concern advances in understanding vestibular function for multi-sensory integration and action, which is extremely relevant to clinical neuroscience, where vertigo symptoms and balance disorders are a major topic.

Figure 9: ESA astronaut Frank de Winne performing the 3D SPACE experiment, testing the differences in perception of dimensions and depth in between normal gravity on Earth and microgravity (Credit: ESA)

Assessment of the past period

Based on the presentation given at the interactions with the ELIPS user community representatives (10–12 January 2012), the brief report, information supplied by ESA, and independent literature and web research, achievements have been noted and criticisms drawn.

During the past five-year period, several high-level scientific studies have been published that have been co-funded by ESA and that have utilised microgravity in the way described above. These studies document the impact that excellent microgravity research can have on the general neuroscience community. However, given the number of researchers and the number of projects currently under way, it is clear that only a minor part of the ESA-funded neuroscience research operates on an internationally competitive level, while the other part, if at all, publishes only in low-impact or specialised journals. Therefore, it is necessary to improve the overall quality of research in this field, for example, by taking the publication record of the PIs more into account during the selection process. Also, more hypothesis-based research and mathematical/computational modelling may help in catching up with the developments in neuroscience in general, but also in neuro-vestibular research, where systems-level modelling has become a ubiquitous tool for formulating testable hypotheses. A re-organisation of the neuro-vestibular Topical Team, which now is, with one single exception, exclusively composed of active PIs, is expected to help improve the overall scientific quality of neuro-vestibular research under the ELIPS programme.

FUTURE PRIORITIES AND RECOMMENDATIONS

NEURO-VESTIBULAR RECOMMENDATION 1:
The label "neuro-vestibular" given to this sub-discipline unnecessarily confines the topic of research that should rather represent a small section of the neuroscience discipline. It is recommended to change the label to "neuroscience", as has already been done in the online Erasmus Experiment Archive, and reflects on-going investigations in various fields of neuroscience, such as motor control in response to microgravity. This will also emphasise the need to invite the general neuroscience community to perform experiments related to the influence of gravity on neural function in general, including sensorimotor, cognitive, cardiovascular, autonomic, etc. This broadening of the scope, which in part has already become apparent, could also help foster closer cooperation with other sub-disciplines such as rodent research, behaviour and performance, cardio-pulmonary, and exercise.

NEURO-VESTIBULAR RECOMMENDATION 2:
Existing facilities to study central-nervous function, such as EEG equipment, should be better promoted (and their use be simplified) to ensure their adequate utilisation.

NEURO-VESTIBULAR RECOMMENDATION 3:
Equipment to generate various levels of artificial gravity between 0 and 1*g*, e.g. a small centrifuge-like off-axis rotator, would generate new experimental possibilities.

NEURO-VESTIBULAR RECOMMENDATION 4:
Since the present neuro-vestibular sub-discipline requires human subjects, crew time is a major bottleneck. There are two possible solutions and both should be pursued. 1) Animal research should be done whenever possible; many questions in neuroscience can be answered at least in part by appropriate vertebrate animal models. 2) Better allocate sufficient crew time to a few excellent projects rather than dividing it up over too many projects, causing experiments to lose quality.

3.2.5 Immunology

Introduction

The prominent role of a healthy immune system is to protect an individual from invasion and colonisation by pathogenic microorganisms and to contribute, through its innate mechanisms, to wound healing and tissue regeneration.

Space relevance and value of the ELIPS programme

As in most human diseases, functional impairment of an individual's immune system is the result of a complex interaction between genetic and environmental factors, both of which must be defined in greater detail for proper implementation of countermeasures aimed at preventing the occurrence of diseases due to immune-dependent processes during long-duration missions. The dissection of complex genetics in populations, through whole genome sequencing and accurate genetic screenings, will be needed to detect individual predispositions to infectious diseases resulting from the inheritance of compound, rare allelic variants. Recent work has highlighted the existence of an emerging area of reciprocal influence between immune cells and neuroendocrine factors whose homeostasis can be altered by environmental stressors that were traditionally thought to be unrelated to immune responses, such as emotional stress, day–night light cycles and spatial confinement (all experienced in spaceflight conditions). These factors add a layer of complexity to the problem of predicting how "normal" immune responses can be induced and preserved in humans exposed to the unique environmental conditions found during long-duration space missions. Further investigation of these issues in spaceflight conditions does not only enable a better fundamental understanding of immune system functioning, it also helps address the issue of crew health during long-duration exploration missions.

Achievements of the past period

Drawing a detailed account of what has been accomplished through ESA-supported projects under the auspices of the latest ELIPS programme was difficult, as the information provided was patchy and the available data were dispersed through several prior reports. Given the time lapse between the design of the experiments and their actual implementation inherent in the ELIPS programme, some of the data available through the published work actually refer to past programmes. The present account was drawn by appraising information available through the presentations and summaries made by the user community representatives, the most recent report of the EC-supported THESEUS coordination action, and preliminary reports of ESA-supported projects, such as the IMMUNO study.

Cell-based experiments

A number of studies have been carried out in isolated cell systems. Such studies, most of which have been published in specialised journals during the last three to five years, suggest that microgravity reversibly impairs a number of functional parameters that can be viewed as correlates of normal immune cell functions. These include immune cell proliferation, cytokine secretion, phagocytosis and motility.

Animal experiments

The reported data collectively shows that T-cell distribution and function, as well as gene expression are significantly modified in living organisms subjected to space flight. For example, to explore the effect of the flight environment on immunity, C57BL/6NTac mice were flown on a 13-day space shuttle mission (STS-118). In response to space flight, the animals had a reduction in liver, spleen, and thymus masses compared to ground controls. Selected experiments involved the assessment of gene expression profiles from primary and secondary lymphoid organs explanted from animals upon return to Earth. Together, these experiments demonstrate that space flight induces significant changes in the thymic mRNA expression of genes that regulate stress, glucocorticoid receptor metabolism, and T-cell signalling activity. These data explain, in part, the reported systemic compromise of the immune system after exposure to the microgravity of space.

Investigations in human subjects

To better approach the consequences of multifactorial effects of physical stressors and emotional stress in humans exposed to space flight, further investigations have been undertaken using a battery of elaborated blood, urine and saliva sampling and analyses together with questionnaire-based emotional stress monitoring. Investigations in humans range from very acute gravitational challenges (parabolic flight, illustrated in *Figure 10*) to short- (two weeks) and long- (4-7 months) duration ISS missions showing that space flight conditions can lead to deviations in human immune responsiveness. Testing of peripheral leukocyte subsets from a small number of samples indicated that early T-cell activation and secreted cytokine profiles were variably reduced. The role of other stress-response systems includes the immunotropic endocannabinoid system, shown to be activated under acute gravitational stress condition, as well as in space. Further ground-based studies have also provided further evidence for the interlinking of emotional stress-sensitive immune changes in man.

Perhaps the most relevant weakness of these experiments is that they are rather descriptive in nature and do not allow a clear dissection of the individual contribution of individual "stressors" to the observed alterations. This may be the consequence of: i) only partial coordination and standardisation of experimental settings used in space-flown missions compared to ground-based surrogates of some of the aforementioned stressors (which in some cases has been already been implemented, e.g. ISS vs. Antarctica vs. MARS500); ii) challenges in the implementation of the full experimental design due to operational and logistic reasons, e.g. related to the timing of cell/tissue sampling, which in some experiments occurs at late stages (post-landing); iii) assessment of functional and molecular parameters on bulk cell populations rather than on purified subsets. Research on human subjects suffers from small sample sizes and a lack of systematic approaches to enable large amounts of data to be extracted from the limited biological samples. Overall, however, the data generated in the ELIPS programme form a knowledge base onto which future experiments can be designed and new hypotheses can be made.

Future priorities and recommendations

There is a clear need for a bidirectional flow of knowledge and information between ground-based and space-based research in immunology. A clear-cut definition of what constitutes a healthy immune system is a pre-requisite to design informative experiments to be carried out in humans undergoing long-duration space flight. This can be determined through ground-based experiments. The definition of the environmental conditions potentially affecting immune responses in space is equally important. These conditions include microgravity, prolonged exposure to constrained environments with reduced exposure to pathogens or exposure to unusual pathogens, perturbation of circadian rhythms and/or day–night light cycles, nutritional status, exposure to unusual sources of radiation, and emotional stress linked to the inherent risks of space missions, as well to the psychological consequences of living in a confined environment for prolonged periods. Health-threatening pathogenic microorganisms and the immune response coevolve. Changes in the environment produce ill-defined adaptive or maladaptive changes in the immune system. A profound knowledge of how environmental conditions in space affect the composition and adaptation properties of both commensal and pathogenic microorganisms is intertwined with the understanding of such qualitative and quantitative changes in both innate and adaptive immune responses. By way of an example, given the emerging connection between the microbiota on the skin and mucous membranes or in the gut and a person's overall health, immune status and response to environmental perturbations in the context of diverse genetic backgrounds, experiments should incorporate accurate sampling of commensal microorganisms colonising anatomical barriers that are easily accessible. Metagenomic studies should be planned co-ordinately with immunological studies to assess their reciprocal interactions. The impact of nutritional factors should be incorporated into large, interdisciplinary projects. Some of these stressors and environmental conditions can and should be comparatively assessed in experimental settings on Earth. Genetically engineered mouse models (GEMM) should be constructed in the preparatory stage of experiments to be carried out in space that are specifically designed to address mechanistic questions that can be uniquely addressed in space. This includes the generation of reporter mice as living readouts for the consequences of mechanotransduction, ionising and exciting radiations, microgravity and other stressors that can be modelled and functionally assessed in mice.

It has to be highlighted that the technology developments done on the ground and geared towards the implementation of space experiments provide tremendous potential for immunology research at large, both industrial and academic. Such ground-based studies should focus on the development of methods and instruments that permit global or near-global analysis of gene expression, genotype, epigenome, cell surface and functional phenotype, serum protein composition and so on. For example, automated methods and miniaturised instruments

Figure 10: A view inside the Zero-G aircraft during an ESA Parabolic Flight Campaign (Credits: ESA - A. Le Floc'h)

that measure in much greater depth and breadth the composition and state of the immune system are necessary and would provide much more detail than previous limited tests of serological or cell-mediated immunity. This will enable investigators to conduct broad and deep analyses of gene expression by hematopoietic cells of the immune system, obtained mainly but not exclusively from peripheral blood and increasingly from small tissue samples that can be collected ethically, and then to relate these findings to a person's history and genotype.

SPECIFIC RECOMMENDATIONS

IMMUNOLOGY RECOMMENDATION 1:
Encourage a paradigm shift from hypothesis-driven to data-driven experimental approaches in immunological research.

IMMUNOLOGY RECOMMENDATION 2:
Encourage device miniaturisation and automation.

IMMUNOLOGY RECOMMENDATION 3:
Encourage recording detailed knowledge of the genetic makeup (hap-maps) of individuals undergoing space missions.

IMMUNOLOGY RECOMMENDATION 4:
Encourage accurate definition of environmental factors affecting immune responses in space.

IMMUNOLOGY RECOMMENDATION 5:
Encourage increased use of mouse models in space-driven immunological research.

3.2.6 Nutrition and metabolism

Introduction and general statement

The health of populations is deeply associated with the impact of ageing and chronic diseases (e.g. cancer), themselves related to sedentarism, food intake and nutritional status, gene expression, and exposure to ionising radiations.

Four observations should be highlighted:

1. Nutrition and physical activity play an important role on health by modulating gene expression, energy balance, oxidative stress and inflammation, and metabolic syndrome;
2. Physical inactivity (bed rest study) has been shown to reproduce the pathological metabolic features observed in overweight and obesity;
3. Specific nutrients (e.g. glutamine, fatty acids) have been associated with stimulation or inhibition of cancer cell growth, as well as with a modulation of the effect of ionising radiation on tumours;
4. Food profile and changes deeply influence the gut microbiota, which in turn modulates the body's metabolic homeostasis, immune competence, response to stress and inflammatory status.

These observations provide important data in the current scientific and societal debate regarding the respective roles and importance of ageing, sedentarism, diet, gene expression and exposure to ionising radiation in the management of the population's health.

Space relevance and value of the ELIPS programme

Only the two facilities supported by ESA (at DLR and MEDES) are able to conduct bed rest experiments. Bed rest experiments represent the best option to explore the impact of sedentarity on health. Taken as a whole (all teams combined), they are the more complete and integrative studies currently performed in humans. They are published in the best journals of the field (e.g. *Am. J. Clin. Nutr.*, *Diabetes*, *Am. J. Physiol.*, *JCE&M*, *Progr. Lip. Res.*, etc.). These studies are needed: i) to develop systems to allow real-time assessment of energy balance and efficacy of countermeasures; ii) to determine proper food allotments; iii) to determine requirements of micro- and macro-nutrients; and iv) to assess changes in eating behaviours.

Chronic exposure of humans to ionising radiation is highly interesting in the of study ageing processes and development of preventive measures such as modified food profiles. It is ethically not feasible in GBR and justifies space experimentation, with good potential of return on investment in ground medicine.

Achievements of the past period

The "non-exercise activity component" (NEAC) of the daily activity energy expenditure (i.e. spontaneous physical activities) is critical for energy balance. Indeed, NEAC is far more important than energy intake and is the buffer that allows the energy balance in response to energy unbalance induced by physical exercise. Too much physical exercise, when deficient in spontaneous physical activity, leads to body mass loss because energy intake is not stimulated, even in the long term. This provides interesting cues i) to suggest for the first time that the physical exercise used for countermeasures in space in ground medicine needs re-evaluation, as so far it is programmed upon the classical dogma of exercise physiologists: the more the better; and ii) to understand the lack of effects of exercise training in the treatment of obesity.

Figure 11: Bed rest subject undergoing indirect calorimetry measurements to assess substrate oxidation and energy expenditure following the ingestion of a meal (Credit: S. Blanc)

Physical inactivity reproduces the metabolic features observed in overweight and obesity. This provides important data in the current debate regarding the respective role of sedentarity, diet and gene expression in the development of obesity.

Physical inactivity triggers oxidative stress and inflammation (low grade), both of which play a role in muscle atrophy and insulin resistance and fat metabolism.

Energy unbalance, either too positive or too negative, triggers muscle atrophy.

Protein supplementation stimulates protein synthesis and bone degradation due to the oxidation of sulfuric fatty acids.

Skin plays a major role in storing sodium in response to high sodium diets and has been implicated in the between-subject variability to sodium.

Space sciences provide mechanistic and original insights into ageing and the sedentarity related diseases.

FUTURE PRIORITIES AND RECOMMENDATIONS

NUTRITION AND METABOLISM RECOMMENDATION 1:

Maintain European leadership in bed rest studies, in particular in relation to countermeasure developments relevant for ground medicine and space flights.

NUTRITION AND METABOLISM RECOMMENDATION 2:

Test a new generation of countermeasures focused on cell alterations (e.g. DNA damage, lipid peroxidation) and tissue atrophy (e.g. sarcopenia, osteoporosis).

NUTRITION AND METABOLISM RECOMMENDATION 3:

Test the interactions between the exposure to ionising radiation, modifications of food profiles (e.g. fatty acids, phenolic compounds) and changes in the gut microbiota.

3.3 Biology and Radiation

3.3.1 Cell and molecular biology

Introduction

The effects of gravity on living systems (single cells, multicellular organisms) are still quite poorly understood at the fundamental science level. However, this scientific area impacts upon all forms of living systems ranging from single-cell studies to astronaut health and well-being. The cellular and molecular biology sub-disciplines (presentation/summaries provided) thus addressed three main, but very broad, topics that need much improved scientific and technical understanding: how/why single cells respond to gravity; gravisensing (mechano-sensing), and life support systems facilitating astronaut-related health/welfare on long-duration spaceflights. Given the breadth of the subject areas, the overview/supporting materials provided covered: a wide range of scientific and technological approaches currently either in place (including relevant/newer technologies) or being contemplated (i.e. to either introduce to or apply in spaceflight); a summary of existing ISS and related facilities/capabilities; and additional technological infrastructure needed to improve the quality of the science in space.

A major emphasis in this discipline was placed on mechanobiology and mechanoperception, how this ultimately results in mechano-adaptation, and the technologies that can be applied to their study. Other issues focused upon the need to consider faster, cheaper and simpler studies in the space/microgravity environment, and innovative approaches associated with these opportunities. A plea was made to develop a European Mechanics Lab, and to develop a rodent (mouse) facility to achieve the best science possible in the spaceflight environment.

Space relevance and value of the ELIPS programme

The space-flight environment has several areas of relevance to ground-based research. These include improved understanding of factors affecting bone and muscle loss, impaired immune responses, radiation damage, and how these processes in space compare and contrast with ground-based systems being studied worldwide.

Assessment of the past period

The visual materials and overview slides provided were largely devoted to broadly utilising and/or addressing existing technologies and capabilities to address pertinent scientific areas in cell and molecular biology, and the technological requirements for the future. One broad emphasis was "Lighting up the mechanonome: understanding the role of force, mechanics, and biological machinery – the mechanonome". This approach was being considered holistically, from cell to mechano-perception to mechano-transduction to mechano-adaptation, including the associated signalling processes and adaptation/responses. All forms of "-omics" research also came under this umbrella. Specific questions included, but were not limited to: how do single cells perceive *g*?; how do single cells adapt to weightlessness?; how are cells affected by cosmic radiation?

Other areas largely dealt with topics such as bone loss and the need for more mammalian (rodent) work. The way in which this information would apply to astronauts, in terms of studies of space-induced osteopenia/osteoporosis, muscle atrophy, radiation damage and reduced immunological responses in space was also briefly rationalised. Rodent work would also help facilitate studies on countermeasures for astronauts on long-duration space-flight.

Some of the technologies being applied/considered overall included: use of optical tweezers to study bone cells; application of atomic force microscopy for biological work in centrifuges; measuring cell local forces; study of endothelial cells in centrifuges; live cell imaging; root hair microtubules in *Arabidopsis*; kinesis and molecular motors; calcium in *C. elegans* muscle; space and ageing; primary human foreskin epithelial cells (cells become stiffer as ageing occurs).

An overview of existing facilities/capabilities was also briefly provided: these included Biobox and KUBIK. The large centrifuge for ground studies and opportunities to carry out research using this and

Figure 12: Astronaut Frank De Winne works in the Microgravity Science Glovebox on the ISS (Credits: NASA/ESA)

other facilities were also described, including a tour of the centrifuge facility. There was a perceived need to develop a European Cell Mechanics Lab, as well as obtaining a mouse facility, with the latter being the key recommendation of the sub-discipline. There were unique telemetry capabilities available.

The sub-discipline also indicated there was much to learn from commercial entities; for example, it was possible to pay 20,000 euros to fly some experiments commercially, and there was access to some limited capabilities/equipment, such as a microplate reader (Nanoracks, USA (TX) for example). There was also a need expressed to think of faster, simpler, and cheaper experiments. Opportunities for new space activities might also arise with XCOR, Virgin Galactic and other entities.

Achievements

The presentation materials above largely focused on technologies/equipment/facilities, with only a brief conceptual overview given to the types of scientific questions that could be and were being addressed. Subsequent documentation was provided that later addressed some of the scientific progress partly associated with the ELIPS programme. Lists of publications in the last ten years in related areas were provided: cell and molecular biology/rodent research; microbiology/bacteria/ yeast; clinostats, random positioning machines; and rotating cell wall vessel bioreactor/high aspect ratio vessel.

The various areas (highlights) of scientific progress and achievements were largely with animal and bacterial cell lines, and used various 'omics' technologies including microarrays and proteomics.

Examples of success stories included: demonstration *in vitro* that osteoblast (or precursor) cellular differentiation in microgravity involved various matrix proteins, and that osteoblast differentiation was impaired in microgravity with various gene expression changes being noted. In addition, NO was found to be important in cell mechanosensing and mechanotransduction.

Bone marrow (mesenchymal) stem cell proliferation was also impaired in microgravity, with 1599 genes having their expression patterns affected.

Studies of endothelial cells (ECs) in simulated microgravity resulted in tube wall formation, perhaps accounting for cardiovascular problems for astronauts on return to Earth. Changes in growth factor secretion and signal pathway activation of ECs also rapidly occurred on parabolic flights.

Thyroid cells were found to be affected in microgravity and this may have downstream effects on bone mineralisation, muscle tropism, fat deposition and left ventricle function. Simulated microgravity with these cells resulted in 235 different proteins being affected, with 37 of these first noted for thyroid cells.

Effects on the immune system were studied in microgravity, with lowered T-cell activation, lower monocyte response, and cytoskeletal structure being altered. However, how immunosuppression occurs is still not well understood. Other studies associated with the immune system involved activation of 5-lipoxygenase (5-LOX) in the apoptotic programme, with effects on mRNA, DNA fragmentation, and protein expression being noted.

Cellular studies were concluded on isolated vascular smooth muscles to better understand redistribution of blood volume and blood pressure with astronauts. Areas investigated were whether these cells were sensitive to gravitational forces and whether blood pressure changes affect the ryanodine molecular target. It was found (using rats and mice) that the responses to microgravity reduced expression of this receptor.

Another highlight was the effects of the microgravity environment on particular bacteria and yeast (*S. cerevisiae*) as a eukaryotic model organism. Changes in virulence, metabolism, growth (reduced), cell wall morphology, cell content, sexual reproduction, gene and protein expression/production were noted. However, the underlying reasons are not yet well understood, with the consensus that a systems biology approach is needed to resolve such questions.

A somewhat extensive bibliography was also provided highlighting the importance (and progress made) in cell and molecular biology publications. Most of these targeted various '-omics' technologies and were largely mammalian studies, with a smaller number of bacterial and yeast investigations. One important finding using *Salmonella typhimurium* cells was that a global regulator, *Hqf*, was identified. None of the bibliographical references apparently involved plant cells.

It was, however, difficult to ascertain precisely what role ESA had in many of these studies, as ESA was only acknowledged in a subset of the reported publications.

Troubleshooting and bottlenecks

The scientific and technical capabilities on ISS are currently quite restricted, relative to non-space-scientific endeavours worldwide. This could be alleviated substantially if the following capabilities could be made available: ability to measure dynamic fluorescent signals in cells exposed to microgravity and centrifugal samples (from plants, larvae, cells, etc.); facility to thaw frozen cells and grow them on flat surfaces to minimise effects of mechanical stresses during launching; multi-passage cell-culturing; in-flight analysis of gene expression; electrophysiological tools to follow ion currents in living cells; and large greenhouse capabilities on ISS. The cell and molecular biology researchers could thus benefit from better instrumentation/capabilities on ISS, such as: confocal/fluorescent microscope; gas chromatograph; mass spectrometer; PCR; RT-PCR; and atomic force microscope. This sub-discipline also provided a very extensive list of equipment needed to conduct ground-breaking work on the ISS, the absence of which limited current studies.

The main point to be made is that the best /most modern science cannot be done until the capabilities on ISS and other platforms keep up with ground-based science activities and instrumentation.

Criticisms

Technological and equipment needs were mainly emphasised, rather than focusing on the scientific progress that had been made, and the vision/large questions remaining/needing to be addressed.

FUTURE PRIORITIES AND RECOMMENDATIONS

CELL AND MOLECULAR BIOLOGY RECOMMENDATION 1:

Topical team(s) to study systems biology, processes in cell biology and related endeavours should be set-up. Topics for investigation could include: studies of single cells and single molecules; signalling cascades; mechanosensing and mechanotransduction in cells and organs; gene regulation induced by microgravity in animals at difference development and age stages; and development of tools to study/ascertain the threshold for mechanosensing. The systems biology approach would utilise transcriptomics, DNA microarrays, proteomics, and other '-omics'.

CELL AND MOLECULAR BIOLOGY RECOMMENDATION 2:

Scientific pursuit in these areas could be much better articulated and justified by clearly distinguishing: (i) activities and approaches with an absolute need for space-flight research/development; and (ii) those involving ground-based (mainstream science) research/development and that of simulated micro- and hyper-gravity effects. Clear statements and rationale of the need for equipment and facilities (see "Troubleshooting and Bottlenecks" above for examples) should be made a priority.

CELL AND MOLECULAR BIOLOGY RECOMMENDATION 3:

Other areas of high priority that should be further considered include: accessing high-level and broadband platforms (imaging centre, transcriptomics, post-translational protein modification, sequencing, etc.); data bank and data sharing facilities for tissue engineering to develop artificial organs, tissues such as vessels, and cancer research; improving on late access times.

3.3.2 Gravitactic and phototactic responses in microbes

Introduction

Gravitaxis and phototaxis are essential processes to understand in the context of space flight. This holds true in particular for microbes where both their small size and lack of differentiated and specialised tissues impose challenges to sensing and responding to gravity and light. For example, the unicellular flagellate *Euglena gracilis* orients itself in the water column with respect to external stimuli such as light, oxygen pressure and gravity, and exhibits a positive light and negative gravitational tactic response. Studies on *E. gracilis* have provided quite a substantial body of molecular information on these processes, e.g. a blue-light-activated adenylyl cyclase that mediates photoavoidance in *E. gracilis* has earlier been identified.

For gravitaxis, there is a large gap in the mechanistic understanding of the process in unicellular microbes, and it is even debated if microbes possess any internal specialised sensing system. In fact, a lot of research on *Paramecium* indicates that the negative gravitational effect might only be due to physicochemical mechanisms (depending on cell shape and medium drag). However, a mechanism in *E. gracilis* has been proposed by ELIPS-supported researchers in which mechano-sensitive channels are activated upon deviation from a vertical swimming direction.

Space relevance and value of the ELIPS programme

On the practical side, the main relevance of this research is found in the culturing of algal communities in space, either for nutritional, water treatment or biofuel aspects. For long-duration exploration missions, it is certainly conceivable that systems based on algae could be used. The practical use of this research on the ground is mainly the identification of genes and their protein products that respond to changes in gravity for biotechnological applications.

Assessment of the past period

Achievements

Early on in this programme, involved researchers developed a methodology for tracking moving cells in the gravitational field (WinTrack2000; GIT Imaging Microsc 1:5). The system is based on a horizontally mounted microscope so that the cuvette is oriented in a vertical position, enabling studies of gravitactic cell movement in combination with sophisticated software for simultaneous tracking the movement of many cells. The WinTrack2000 system has subsequently been used for more recent ground-based molecular studies on gravitaxis. In two publications, the authors identified the genes involved in gravitational sensing and signalling in *E. gracilis*. First, the gene encoding a transient receptor potential (TRP) family channel protein was cloned and sequenced. RNA interference (gene knock-down) confirms that these channels are involved in graviperception, since in the knock-down mutant gravitaxis was abolished. Secondly, they identified DNA sequences of five calmodulins, which are calcium-dependent signalling components. In a functional analysis, the biosynthesis of the corresponding proteins, CaM.1–CaM.5, where the inhibition of CaM.2 resulted in a loss of gravitational response, not observed for the other calmoduline isogenes. Thus, the authors could convincingly display that the calmodulin genes were differentially involved in the gravitactic response. These results have led to a working model for the gravitactic response in *E. gracilis* based on the influx of calcium ions mediated by the activated mechanosensitive TRP channels resulting in an increased intracellular calcium concentration that stimulates CaM.2. The activation of CaM.2 is believed to activate an adenylyl cyclase and results in enhanced production of the secondary signalling molecule cAMP, which in turn activates down-stream components to alter the moving direction.

Criticisms

Euglena cultures have flown on both sounding rockets and parabolic flights. However the committee found most of the work performed over the past years to be ground-based. Despite the fact that most of the results are exciting and relevant, it is surprising that the results are not published in higher ranked journals. It is mentioned that a limiting factor for high impact publications would be the limited number of replications; however, that should not be relevant in this case because all their data have been collected on the ground.

FUTURE PRIORITIES AND RECOMMENDATIONS

Based on the current progress in the programme, a couple of general and specific recommendations can be made for the future.

GRAVITACTIC AND PHOTOTACTIC RESPONSES IN MICROBES RECOMMENDATION 1:

The genetic manipulations performed in *E. gracilis* are essential for proving the functional importance of specific genes. This is currently performed by a transient gene knock-down technology (RNAi). It is to be expected that in the near future, proper gene knock-outs could be made in this organism, and this methodology should then rapidly be embedded in the investigations performed.

GRAVITACTIC AND PHOTOTACTIC RESPONSES IN MICROBES RECOMMENDATION 2:

The gravitaxis studies in *Euglena* should be extended to involve one or two other relevant and evolutionary distant organisms. A suggestion would be filamentous fungi, where several species can detect and respond to both gravity and light. In addition, these fungal systems are amenable to genetic manipulation and would potentially bring new functional information to the current working model on gravitaxis.

GRAVITACTIC AND PHOTOTACTIC RESPONSES IN MICROBES RECOMMENDATION 3:

Bringing modellers/theoreticians into the project would provide a systems biology approach to gravitaxis. In particular, this would allow for interesting modelling of the working hypothesis and bring a wider interdisciplinary community into the group. In addition, the model should try to encompass signalling interactions – in this case between the gravitactical and light responses. The only way these questions can be experimentally proven is to go to space and investigate the phototaxis response in wild-type and specific signalling/sensing mutants.

GRAVITACTIC AND PHOTOTACTIC RESPONSES IN MICROBES RECOMMENDATION 4:

The microscopy system for studies on gravitactic responses should become an open facility for ground-based research in general (at least for space relevant projects) and should be open for other researchers to utilise. It should also be adopted and used for space flights. Having this microscopy system in space would allow for similar kinds of gravitational studies on other unicellular algal systems and be a good avenue for fast-track AO calls in the future for space research.

3.3.3 Microbiology

Introduction

Since the late 1950s, space technology has developed spacecraft for transporting terrestrial life into low Earth orbit (LEO) to study the life forms' responses to selected conditions of space in situ. The two most influential physical factors experienced on board an orbiting spacecraft are the state of near-weightlessness (microgravity) and the increased radiation exposure incurred as a consequence of being outside Earth's protective atmosphere. Experiments in space have also been complemented by studies using terrestrial laboratory facilities designed to simulate selected parameters of outer space, such as microgravity via clinorotation. Within the space capsule, microgravity and/or cosmic radiation were the main parameters of interest to study. It should be noted that gravity can produce two effects on an object as a function of its mass: displacement (motion) and/or deformation (weight).

The majority of investigations to date have indicated that microgravity has an influence on microbial growth and behaviour. The mechanisms responsible for the observed biological responses, however, are not yet fully understood. It is clear that microgravity has a direct effect on the environment surrounding the cell simply due to the fact that there is no convection, only diffusion. This suggests that in microgravity, the observed changes in microbial growth and behaviour can be indirect.

Future studies focused on microbial behaviour (e.g. biofilm production, antibiotic resistance, etc.) in conjunction with genetic studies on regulation of the genes known to be involved with a particular behaviour will lead to a clearer understanding of the role that gravity plays in microbial growth, development and behaviour. While the exact mechanisms of action of microgravity on prokaryotes have not yet been fully determined, the proposed gravity-driven cascade of events may be summarised by 1) beginning with an altered physical force acting on the cell and its environment upon exposure to microgravity (the 'gravity trigger'), resulting in 2) reduced extracellular transfer of nutrients and metabolic by-products moving towards and away from the cell, that consequently 3) exposes the cell to a modified chemical environment; the sum of which ultimately gives rise to 4) an observed biological response that differs from that which occurs under normal conditions (1*g*). For bigger eukaryotic cells, especially those possessing a cytoskeleton, microgravity has been shown to have a direct effect on cell behaviour (division, signalling, etc.).

The main objective of the ELIPS investigations presented is to obtain a comprehensive understanding of the importance of gravity and various stresses in space on the formation of organised cell structures in microbes. Invasive growth on solid media is considered to be a means for non-motile cells, like yeast, to forage for nutrients or to colonise hosts. In addition, an understanding of both regulatory and metabolic changes in microgravity in yeast will have an impact on our understanding of the effects microgravity has on life in general.

Space relevance and value of the ELIPS programme to microbiology

The yeast *Saccharomyces cerevisiae* has developed into the key model organism for a wide array of general basic questions in cell biology, e.g. replication, DNA repair, signalling, transcriptional activation, etc. The immense base of functional information on this organism, provided by both genetic and biochemical studies, puts it in a unique position for systems biology studies on regulatory and metabolic networks. In this respect the choice of *S. cerevisiae* as a model organism to understand molecular mechanisms in operation in space is certainly highly appropriate. In addition, the knowledge generated under microgravity has the potential to be of great importance for the vast yeast community in basic science.

The relatively high density of yeast cells, which makes them sink in non-stirred fermentations, is a practical aspect of yeast growth that is relevant for its use in space. For this reason, it is to be expected that large-scale fermentations in space would be quite different compared to cultures on the ground. Today, yeast is used extensively in various biotechnological applications (e.g. heterologous production of pharmaceuticals, production of biofuel, beer and bread), and its high density is expected to impose changes in large-scale fermentation in any of these applications.

Figure 13: The Biolab is a facility designed to support biological experiments on micro-organisms, cells, tissue cultures, small plants and small invertebrates (Credits: ESA - D. Ducros)

Assessment of the past period

Achievements

A major asset is that microbiology research has incorporated new -omics technologies (proteomics, transcriptomics) to provide a global picture of the physiological changes in yeast under microgravity. An initial proteomics study has been published, which reports a shift in metabolism during space flight leading to a higher degree of fermentation compared to respiration. The follow-up study is a transcriptomic analysis using DNA microarrays for gene regulation in space (to be published). Studies have also been recently conducted to identify genes of importance for growth and survival in space using the available genome-wide collection of gene deletion mutants.

Researchers have also developed a novel system called the Biocontainer to follow growth in space and allow (manually) high-resolution images to be takens. This system has been used to investigate to what extent microgravity has an impact on growth in yeast, e.g. growth rate, invasive growth, colony spreading. Interestingly, under microgravity, the Σ1278b strain showed reduced invasive growth.

S. cerevisiae possesses a remarkable capacity to adhere to other yeast cells, which is called flocculation. This phenomenon is based on the fact that yeast cells adhere in clumps and sediment rapidly from the medium in which they are suspended. The cell–cell interactions are mediated by a class of specific cell wall proteins called flocculins (FLO genes). The group has provided functional information on the FLO1 gene.

Publications on these studies have addressed the use of a proper control. This is not a trivial issue and there are a great number of experiments in space that do not fully implement a proper control, leading to false conclusions. The temperature in space was followed and the recorded profile was mimicked in a ground control sample. During the presentation to the committee, it was also stressed that the use of 1*g* control in space has now been adopted, which is certainly the most relevant control and should be highly encouraged in any kind of space-related microbial study.

Criticisms

High resolution photography was only possible with manual photography and therefore images could only be taken at a limited number of time points. Only two images were taken in space at two distinct time-points with the Biocontainer. More frequent sampling would surely have provided a much more detailed description of the growth impact. In addition, this research has the potential to appear in journals with high impact, which so far has not been the case. More emphasis should be given to the systems biology aspects of microbial responses to microgravity.

FUTURE PRIORITIES AND RECOMMENDATIONS

MICROBIOLOGY RECOMMENDATION 1:

A much stronger systems biology aspect should be incorporated into the investigations. This is particularly valid for the vast genome-wide data that is being generated in space. Setting the recorded regulator changes in perspective will be a major challenge in the future and will require close links to theoreticians/modellers.

MICROBIOLOGY RECOMMENDATION 2:

Investigations should be linked to further laboratory automation, which is a challenge in particular for -omics related data. The lab-on-a-chip approach is well suited for yeast studies, and yeast would in this context provide a good raw model for these types of developments, based on the great amount of background information available. Automation of -omics data is an important development that could be implemented not only for microorganisms but also for higher, more complex systems.

MICROBIOLOGY RECOMMENDATION 3:

Another important future development includes tools for following dynamic processes in cells in real time under microgravity conditions. An important resource in yeast is a complete collection of GFP-tagged proteins, enabling production, localisation and degradation studies in real time. The development of this kind of high-resolution microscopy and online imaging system would certainly open up many new avenues for interesting high-resolution studies in cell biology in space.

MICROBIOLOGY RECOMMENDATION 4:

The completely sequenced clean lineages of yeast in functional studies should be utilised, which will highlight and give important information on the impact from the genetic background to various responses to microgravity.

3.3.4 Astrobiology

Introduction

Astrobiology addresses three basic questions that have been asked in various ways for generations: how does life begin and evolve, does life exist elsewhere in the universe, and what is the future of life on Earth and beyond? Accordingly, the discipline of astrobiology is broad and encompasses the search for life within and beyond our Solar System, laboratory and field investigations of the origins and early evolution of life, and studies of the potential of Earth life to adapt to future challenges, both on Earth and in space. These studies require an interdisciplinary approach that combines molecular biology, ecology, climatology, geology, geochemistry, planetary science, astronomy, astrophysics, information science, space exploration technologies, and related disciplines. The broad interdisciplinary character of astrobiology compels one to achieve the most comprehensive and inclusive understanding of biological, planetary and cosmic phenomena.

These three broad questions can be sub-divided into smaller specific questions particularly relevant to ELIPS, including: what are the environmental limits of terrestrial life and the biosphere? How did life evolve radiation protection mechanisms? Can life be transferred between planets? How will changes in the Earth's biosphere affect life today and in the future?

Space relevance and value of the ELIPS programme to astrobiology

Space experiments coupled to ground experiments

Two major questions of astrobiology are, does life exist elsewhere in the universe, and what is the future of life on Earth and beyond? These questions can only be answered by conducting research in the space environment aboard spacecraft (e.g. BioPan, shown in *Figure 14)* and in planetary environments other than Earth's. It should be made clear that the space environment and planetary environments other than Earth's (especially with respect to radiation and gravity) cannot be duplicated accurately by simulation chambers on Earth. Earth-based simulation studies are valuable for obtaining preliminary data in advance of a space mission and for better interpreting data from space missions. Therefore, the only way to study the survival of organisms in space and planetary environments convincingly is to send them into space, whether on platforms in low Earth orbit or beyond. For example, space experiments coupled with ground control and simulation experiments provide data leading to a better understanding of the biochemical and physiological limits of life. Such data give insights into the genetic basis of radiation and desiccation damage.

Application potential

Additional important questions in astrobiology include, what is the fate of biological systems beyond Earth, and, more specifically, can habitats be developed that allow humans to live beyond Earth? These questions are being addressed by studies on the effects of different gravity regimes (including microgravity), radiation, and desiccation using microorganisms as model systems. Because microorganisms form the foundation upon which habitable environments depend, data from these studies can be used to design and develop sustainable habitable environments for humans beyond Earth (e.g. bioregenerative life support systems). In the quest for human habitation beyond Earth, data

Figure 14: Installation of Biopan on the exterior of the Foton re-entry capsule (Credits: ESA - S. Corvaja 2007)

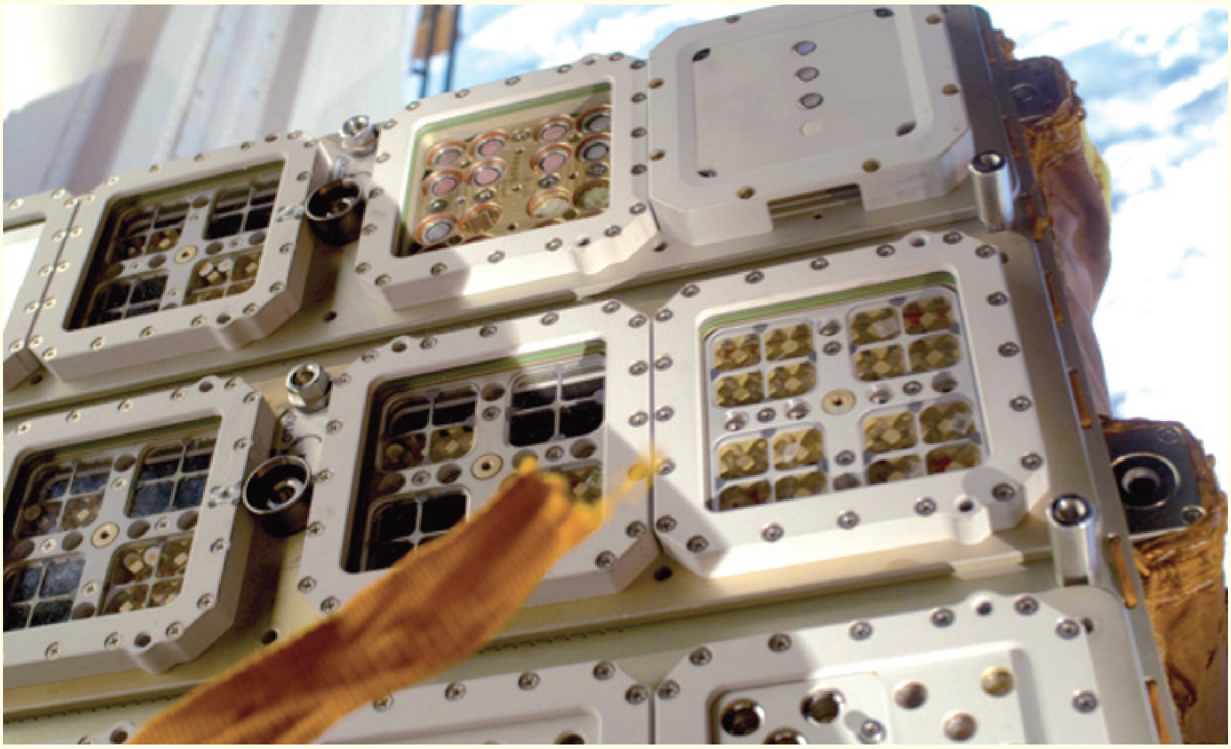


Figure 15: The Expose-R facility, attached to the outside of the ISS, is loaded with a variety of biological samples being exposed to the harsh environment of space (Credit: ESA)

from astrobiology experiments exposing organisms that have been engineered to perform certain useful functions to the rigors of the space environment will be necessary (e.g. bio-mining, biocementation, etc.).

Assessment of the past period

The primary source of information on the ELIPS programme relevant for this report was the overview presented at the workshop with representatives from the ELIPS user community (10-12 January 2012).

Achievements

The astrobiology programme has had several successes during the past few years including a BioPan flight as well as the EXPOSE E and R flights aboard platforms outside the ISS. In association with these missions there has also been substantial ground-based research on the effects of the simulated space environment on microorganisms, and on organic molecules found in the interstellar medium thought to be important for the origin of life. For example, new insights into mechanisms of radiation damage in microorganisms exposed to space conditions were found during the EXPOSE and BioPan experiments. The EXPOSE (shown in *Figure 15*) and BioPan facilities have expanded the numbers and types of organisms exposed to the space environment and thus expanded knowledge on the kinds of organisms and communities that can survive exposure to the space environment (e.g. bacteria, archaea, eukarya). The astrochemistry experiments revealed the complex chemistry that can occur in the space environment, providing insight into mechanisms for the production of molecules thought important for the origin of life. The results of the most recent of these experiments are to be published in an upcoming issue of the *International Journal of Astrobiology and Astrobiology*. Data from a number of these studies helped lead to the development of new protocols and standards for planetary protection for missions to other Solar System bodies. In addition, the ESA Life Sciences programme was instrumental in forming EANA, a network of 19 nations involved in astrobiology, and the development of ABCNet, an astrobiology lecture course.

Criticisms

The astrobiology community has conducted much of the same type of space exposure experiments on microbes, biomolecules, and organic compounds thought to be important for the origin of life in low Earth orbit. Additional simple exposure experiments in low Earth orbit will add little to our knowledge base. It is time for the community to take a broader approach in its experiments (for example, asking such questions as what is the effect of the radiation that would be experienced on another body of the Solar System on population dynamics of a microbial community, and how does altered gravity affect nutrient flow through a microbial community?). AOs in the ELIPS programme should reflect this new research concept in calling for studies on more complex systems.

FUTURE RECOMMENDATIONS

As a high priority, the astrobiology community should go beyond low Earth orbit to conduct experiments outside and inside spacecraft, especially in interplanetary space aboard returnable and non-returnable spacecraft. When mission opportunities arise, exploration of the surface and subsurface of other planetary environments for life should become an extremely high priority. Additional recommendations include the following.

ASTROBIOLOGY RECOMMENDATION 1:
Based on past and current experience, continue to develop new orbital exposure facilities both inside and outside spacecraft. Develop systems capable of *in situ* monitoring of microbial growth in Earth orbit (e.g. Cubesats).

ASTROBIOLOGY RECOMMENDATION 2:
Develop access to space beyond low Earth orbit to allow for experiments in more realistic interplanetary radiation environments.

ASTROBIOLOGY RECOMMENDATION 3:
Develop facilities that mimic temperatures found in the interplanetary environment and on other planetary bodies for ground- and space-based research.

ASTROBIOLOGY RECOMMENDATION 4:
Accelerate the development of and access to new astrobiology research facilities from the time of proposal acceptance to the time of implementation.

ASTROBIOLOGY RECOMMENDATION 5:
Improve access to ground-based facilities as well as the support to use them.

ASTROBIOLOGY RECOMMENDATION 6:
Implement mechanisms to allow interaction with other ELIPS domains such as physiology/microbiology, to learn from common experiences, develop common instrumentation, and prevent duplication of experiments.

3.3.5 Plant biology

Introduction

Gravity is known to influence plant growth and development, notably in terms of: root and shoot orientation/tropisms; ability of the photosynthetic canopy and branches in woody plants, for example, to align/orientate themselves in a way to optimise the capture of sunlight to power photosynthesis; the ability of woody stems in trees to attempt to maintain a vertical alignment through production of specialised tissues of support (so-called reaction wood) and also for branches to adopt different orientations outside of the vertical alignment, which allows branches to extend the overall breadth and range of sunlight energy capture via enlargement of the photosynthetic canopy.

Space relevance and value of the ELIPS programme

The various plant tropisms experienced on Earth help define the physiological fates of different cell types/organs in growing plants, and the dynamic changes that can and do occur during growth/development. Studies on plants in microgravity provide an uncoupling of the gravitropic input, and other tropisms and their associated signalling cascades can be studied in the absence of the gravity vector, in facilities such as the European Modular Cultivation System (EMCS) shown in *Figure 16*. Such investigations thus have the potential to identify the components of these cascades, such as with phototropism, for example, and thus to understand the processes that occur when plants are grown on Earth.

In addition, life support systems in space using plants (e.g. as a source of fresh foodstuffs in long-duration missions) grown in a closed-loop environment have Earth-based research ramifications. Potential areas of benefit include bioremediation, carbon dioxide uptake/oxygen release, water and air recycling, removal of toxic components, and sustainable agriculture.

Figure 16: The European Modular Cultivation System (EMCS) is an ESA gravitational biology payload installed on the ISS (Credit: ESA/NASA)

Assessment of the past period

The field of plant biology as it pertains to the effects of the spaceflight environment/microgravity was covered by a presentation and report made available to the committee, and focused mainly upon four areas: gravitropism; other tropisms (including phototropism); abiotic stress; and sustainable plant breeding. The presentation outlined what we could learn and benefit from by studying in microgravity, pointing out that this was the first time in the history of life where the gravitational influence could be removed and tropisms could be studied in "pure form". The emphasis was mainly on the model plant, Arabidopsis, whose genome was sequenced in 2000 (the first plant species to have this done).

Discussions subsequently described TTs and the challenges of conducting experiments on the ISS. Later documentation was provided covering perceived major scientific advances in both flight- and ground-based studies over the last five years, and the needs for the future.

Achievements

The main aspects of the plant biology overview addressed, in a very general sense, the various tropisms above and associated signalling cascades. Topics included the roles of starch granules/statoliths in gravity sensing/responses for root gravitropism, and downstream signalling cascades involving the cytoskeleton/actin cytoskeleton and calcium channels. Some discussion of the potential contact of statolith membranes in roots with membrane-bound receptor molecules located in the plasma membrane was also given, and that this triggers the signal transduction process. Auxins in plant stem bending were briefly mentioned, as was inositol-3 phosphate in signalling pathways. Other topics included: a hydrostatic pressure model; a ligand-receptor model; blue light directing stem growth (phototropins) versus red and far-red light receptors (phytochromes); red light in microgravity having a unique response for hypocotyls; meristematic cell differentiation and cell proliferation; auxin polar transport; cell cycle attenuation, and reactive oxygen species (ROS) increases in simulated microgravity. The life support system MELISSA was also briefly mentioned as well as its potential for sustainable plant breeding.

The main achievements perceived were: establishing that the threshold acceleration perceived in gravisensing was 0.001*g*; seed-to-seed experiments/observations on amplifying effects of increased *g* on circumnutation and the reverse in microgravity; effects of gravity on amyloplast displacement and Ca disruption; effects on proteomic profiles in microgravity, as well as waiving and coiling of Arabidopsis roots. Ground-based studies deemed noteworthy included uncoupling of cell proliferation and cell growth; auxin polar transport partially inhibited in weightlessness; gravitational stress leading to increased levels of ROS.

Troubleshooting and bottlenecks

Main bottlenecks were considered to be too long delays between AOs and experiments; too slow development of hardware; too much paperwork; and questions about what if these studies did not occur.

Criticisms

While sympathetic to the scientific/technical areas being very narrowly focused and specialised, the depiction of activities over the last five years was not, from a general plant science perspective, at the very highest international scientific level. In some cases, studies may not have absolutely required microgravity facilities/capabilities. Some studies apparently lacked a hypothesis-driven aspect and were more phenomenological in design and execution, and the potential quality of the papers published seemed variable. Some were in reasonably good journals, such as *Plant Physiology*, but more often were in very specialised and journals with lower impact factor. Additionally, facilities and equipment on the ISS are not on par for modern day studies in plant science/plant molecular biology/plant biology. There also appears to be a lack of "new blood" coming into the scientific/ technical areas under investigation.

FUTURE PRIORITIES AND RECOMMENDATIONS

PLANT BIOLOGY RECOMMENDATION 1:

New blood must be brought into the field, either via TTs and/or by engaging more broadly the scientists in plant biology who are not regularly involved in space experimentation. A young investigator programme could also help.

PLANT BIOLOGY RECOMMENDATION 2:

Facilities need to be brought up to the standards and expectations of the 21st century. There is a need to have RT-PCRs; use of GFPs in flight; confocal and other microscopies and imaging capabilities; sensors and analytical equipment (nutrient, water, oxygen and carbon dioxide) for real time monitoring of aerial and root zones; systems to detect/manage contamination in flight; better controlled environments for various aspects of plant growth/development (T, radiation, airflow; ventilation, gas composition).

PLANT BIOLOGY RECOMMENDATION 3:

Research programmes should be extended to all aspects of gravitropic responses, including how

different cell types respond. Other emphases are needed on hypergravity. There is also a need to study broader aspects of gravitropic effects in woody plant forms (stem realignment and branching, for example); these seem to be missing at present. More hypothesis-driven approaches are also needed.

3.3.6 Developmental biology

Introduction

Development is generally a robust process, and has to be in order for organisms to survive long enough to reproduce. A key process involved in development is the spontaneous pattern formation arising from activation and inhibition of proteins and pathways that regulate gene expression, that ultimately results in differentiation and morphogenesis of the embryo.

Space relevance and value of ELIPS programme

Under the ELIPS programme, fundamental developmental biology research is being performed through studies of both plants and animals. Understanding plant developmental biology has an added benefit of providing insights for human space exploration, for example for producing sustainable food sources in space. Regarding animal development, the way that development is modulated by the environment, particularly during the very early stages of embryogenesis, is not very well understood, and there is evidence that microgravity can influence the development of specific features such as the vestibular system. It could also have a more profound influence on other central nervous mechanisms such as the development of motor control, spatial orientation mechanisms, and/or the vestibular influence on hippocampal function, even on memory systems. Thus, as in other areas, knowledge gained from experiments on developmental biology in microgravity has the potential to deliver mechanistic insights.

Assessment of past period

Assessment of the past period was based on the presentation and reports made available to the committee. The focus of this material was on developmental biology in animal species rather than plants (developmental biology in plants is reviewed in the report on plant biology).

During the past five years, work carried out under the ELIPS programme has assessed the effect of microgravity on morphological development in fish and amphibians, physiological development in amphibians, morphological development in insects, and patterns of gene expression in developing insects. These studies have shown that there may be critical periods during development where the absence of gravity can have an influence on subsequent structure and/or function. For example, these effects include the development of the vestibular system and the shedding of tails by tadpoles.

Overall, the focus of these experiments was to answer the general question of whether there is an age- (and/or developmental-) related sensitivity to gravity for the development of sensory, motor, and neuronal systems. However, the overall scientific direction of these studies was not always clear to the ESF expert committee, and developmental biology is perhaps one area where consolidation with other areas such as molecular biology and genetics would be helpful. Some data have been published in peer-reviewed journals, but others are not yet published, and so the overall scientific quality was difficult to judge.

FUTURE PRIORITIES AND RECOMMENDATIONS

DEVELOPMENTAL BIOLOGY RECOMMENDATION 1:
Overall, an urgent priority for this subdiscipline should be to encourage a clear review and prioritisation of research objectives for understanding how gravity influences developmental biology of animals and plants. It is important to establish how experiments in microgravity will offer a detailed mechanistic insight into the process of development, and to carefully consider how information at the molecular level will be linked to larger-scale effects such as morphogenesis. Additionally, there should be a broadening of the participation to relevant and productive groups at the forefront of science who have not been involved in microgravity research up until now. This could be implemented through the formation of a TT focused specifically on developmental biology. There should also be a coordinated consideration of what are the best technologies that can be brought to bear.

DEVELOPMENTAL BIOLOGY RECOMMENDATION 2:
It is crucial to initiate a discussion about the question of whether studies in animal developmental biology should be restricted to the cellular level (fertilised eggs, myocytes, stem cells, etc.) or whether also embryos, larvae and juveniles could be included in the search for general principles of development such as critical periods or age-related sensitivities. A clear decision about the use of animals from the embryonic up to the juvenile stages should be implemented in each coming announcement of flight opportunity.

DEVELOPMENTAL BIOLOGY RECOMMENDATION 3:
Once the important research questions have been identified and prioritised, areas having synergy with other programmes (e.g. plant biology, neuroscience) should be identified so that coherent strands of research can be specified within an AO.

3.3.7 Biological effects of radiation

Introduction

The delineation of the stochastic effects associated with human exposure to cosmic galactic radiation (CGR) during space exploration missions outside the magnetosphere is a strong requirement for risk assessment and defining appropriate protection countermeasures. This is particularly true for estimating the late biological effects of CGR such as cancer risk, which appears to be a major health hazard for long-duration manned missions to Mars and for which major risk uncertainties remain. Some other immediate and late biological effects of radiation on humans in space that can be partly prevented by antioxidant intake have also been identified including damage to the central nervous system, immune dysfunction, cataract induction and interference with cardiovascular, digestive and respiratory diseases.

Unresolved key issues include the following:

- The biological effect of heavy ions as the main deleterious components of CGR (in close cooperation with the radiation dosimetry sub-discipline).
- The role of secondary radiation (projectiles and target fragments, neutrons, protons, electrons, etc.) generated inside the space vessel by the interaction of heavy ions with shielding components.
- The still highly debated question of the linear vs. quadratic biological response to low doses of radiation with a possible threshold.
- The possible interference of microgravity in the biological processing of radiation damage to biomolecules, including DNA repair and cellular signalling.

Relevance for space exploration missions

The necessity for better assessment of several health risks for crew members of exploration space missions (as discussed above) fully justifies both Earth- and space-based investigations devoted to the determination of molecular and biological effects of space radiation.

Assessment of past period

One of the key, pertinent radiation biology findings, recently obtained within the ELIPS programme through ground-based accelerator facilities (*Figure 17*), demonstrates the relatively low effectiveness

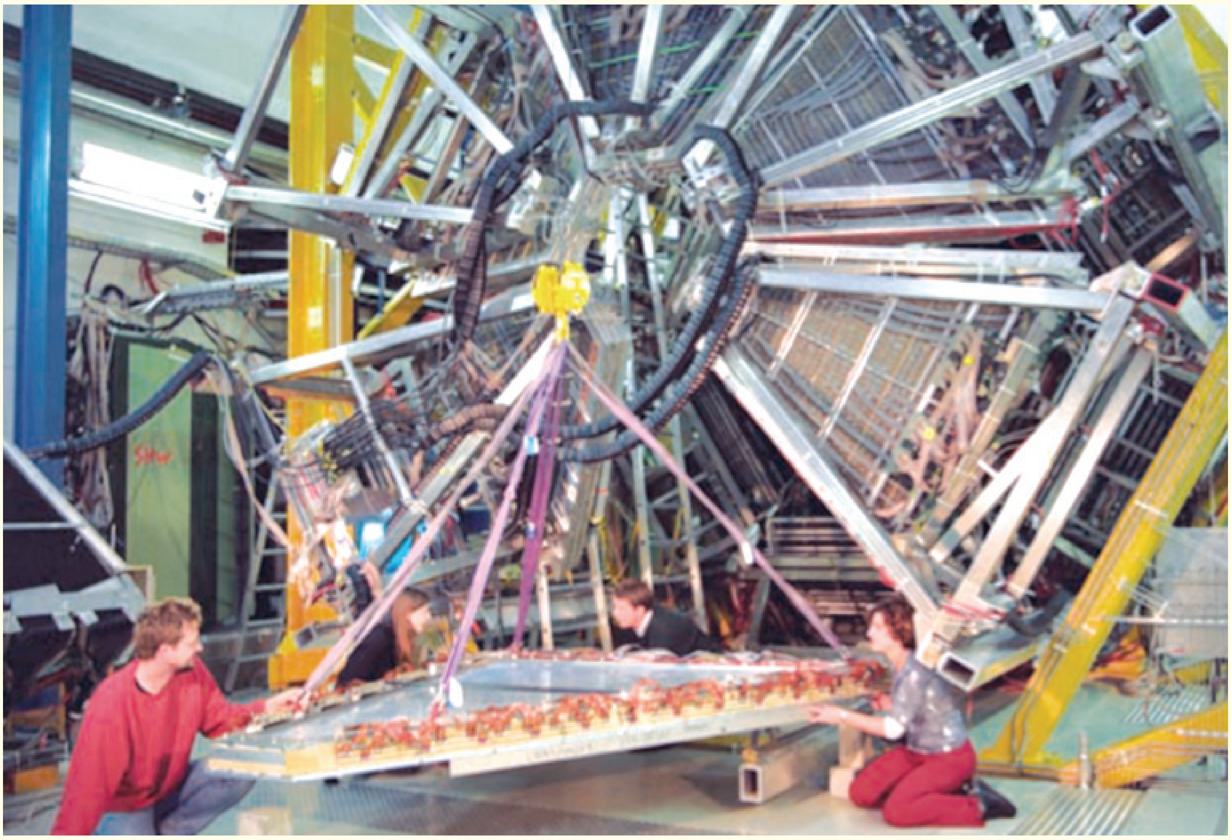


Figure 17: The GSI facility in Darmstadt, Germany operates a unique, large-scale accelerator for heavy Ions (Copyright: GSI Helmholtz Centre for Heavy Ion Research GmbH)

of heavy ions to induce leukaemia. This was achieved using the accelerator facilities provided by the ELIPS platform at the GSI research centre at Darmstadt, Germany. Forthcoming research projects are aimed at gaining missing information on several late effects of CGR and secondary radiation, including the ability of heavy ions to induce solid tumours and to exert hereditary effects. For this, ground facilities will be mostly used.

Trans-disciplinary aspects

It has already been mentioned that CGR is a major health concern for humans during long-term space missions. In addition to cancer risk, there are also possibilities of immune dysfunction and occurrence of several cardiovascular, digestive and respiratory pathologies. There is a strong need to address these issues in a more concerted way with concerned life science sub-groups in order to better assess the contribution of heavy ions among other space environment factors such a microgravity.

Earth benefits and applications

There is an increased use of heavy ions in the treatment of several cancers (hadrontherapy) that are resistant to X- or gamma-ray therapy. Therefore, there is a possibility of synergy with medically orientated studies on both fundamental and applied aspects including mechanisms of heavy-ion-induced lethality, protection and minimisation against side-radiation effects, and occurrence of secondary cancers.

RECOMMENDATIONS

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 1:

Efforts should be made to enlarge the expertise of the existing TTs by welcoming new experts in from the broad, interdisciplinary field of radiation biology (it currently appears to be restricted to a few groups/disciplines). This should attract active research groups involved in radiation biology investigations that are still missing in the present ELIPS programme and build broader research proposal for future flight opportunities. Future proposals should also include interdisciplinary aspects with the immune, cardiovascular and central nervous system communities, particularly when space experiments are concerned.

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 2:

NASA has developed a dedicated space radiation biology research laboratory at Brookhaven National Laboratory and efforts should be made to participate in joint projects by combining complementary expertise for assessing the damaging effects of radiation on the genome. One may also recommend continuing to organise joint international workshops with scientists involved in space radiation biology such as the annual Workshop on Radiation Monitoring for the International Space Station (WRMISS) series.

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 3:

There is also a need to further develop computational modelling and simulations to enable a better understanding of molecular effects of CGR on key cellular molecules and the biological consequences, particularly in terms of late effects (cancer).

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 4:

Access to ground-based research facilities with emphasis on ion accelerators should be facilitated at GSI with a possible extension to GANIL at Caen (France) where a biology laboratory has been created.

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 5:

There is a need to implement equipment on the ISS for performing experiments on animals to further investigate the effect of microgravity on the biochemical processing of radiation-induced cellular damage. For this purpose, animal facilities and radiation sources are required on board.

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 6:

Participation in major scientific events such as the annual or international radiation research meetings by having, for example, a symposium dedicated to space radiation biology should be encouraged. This also concerns the already successful policy of publication of research findings and review articles in journals with a high impact factor.

3.3.8 Radiation dosimetry

Introduction

Accurate physical dosimetry of radiation inside spacecraft and assessment of the dose equivalent are required to correctly estimate the risks associated with human exposure to cosmic galactic radiation (CGR) and secondary radiation during interplanetary exploration missions. Several passive detectors have been implemented on board the ISS through extensive cooperative efforts involving Japan, the USA and several European laboratories through ELIPS, with the aim of delineating and quantifying radiation field parameters (type and energy of the particles together with fluence rates). Modelling each radiation component in the space environment is mandatory for risk assessment, and currently several models are available. This is complemented by improvements in space weather forecasting and the development of transport codes that take into consideration the interaction of primary radiation with shielding materials and human tissues.

Another major field of research involves the development of passive and active shielding to reduce the level of exposure to CGR and minimise the generation of harmful secondary radiation, which consists of projectiles and target fragments together with neutrons, protons, electrons and "bremsstrahlung". Individual protection against deleterious biological effects of radiation also requires investigation of dietary compounds as a countermeasure. However, its value is limited due to the low ability for scavenging radiation-induced reactive oxygen species. The main aim of these complementary approaches, that has partly been achieved, is to come up with a detailed estimation of the radiation dose received by inner organs. This is needed to ensure that human exposure to radiation fields during exploration missions will be kept below predefined acceptable risk limits, mandatory for mission planning and operation.

Relevance for space exploration missions

Assessment of the space radiation environment through measurement and modelling, together with accurate forecasting of solar particle events and the determination of individual dose exposure at the organ level is essential for risk estimation of long-term missions (Moon, Mars) devoted to exploration.

Recent achievements and future developments

Major progress has been made during the last decade on the design of several passive physical detectors including systems based on microdosimetry, silicon-type instruments, thermoluminescent detectors and ionisation chambers that have been tested on the ISS through active cooperation with NASA and Roscosmos and JAXA. Free space radiation components can be monitored and discriminated by several devices. A semi-active detector (ALTEA instrument) that allows real-time assessment of radiation doses received by astronauts during "extravehicular activities" is also available.

Another important achievement deals with the availability of several observation platforms for describing and forecasting space weather, with an emphasis on solar particle events (SPE). Future developments aimed at providing more reliable information are expected from the implementation instruments currently under discussion through an ESA design study in association with the ESA Space Weather Working Team.

Significant advances in the development of models for individual space radiation components have been made in the past years through international cooperative efforts and the design of one- or three-dimensional transport codes that are either deterministic or involve Monte Carlo based calculations. This allows partial delineation of the effects of the interaction of high energetic heavy particles with shielding materials in terms of excitation events and generation of secondary radiation whose biological effects remain to be assessed.

All of the previously addressed achievements have contributed to the determination of individual inner organ exposure to GCR and secondary radiation within the spacecraft, a major objective that has so far been partly fulfilled. This requires consideration of several radiation parameters including relative biological effectiveness. Also, the use of the human phantom MATORSKA on board the ISS has determined dose distribution in human organs during SPE situations. Experiments are currently in progress in the development of novel and more efficient shielding materials with the aim of providing more efficient protection against radiation risk.

Trans-disciplinary aspects

The evaluation of radiation risk on board and outside the spacecraft requires an integrated approach involving mostly physicists for various aspects of dosimetry (detection and modelling of radiation components) and biologists for the assessment of biological effectiveness of particles and the delineation of immediate and late biological effects.

Earth benefits and applications

Scientific activities on space radiation dosimetry have a beneficial impact on the assessment of long-term health risks associated with aircraft crew exposure to radiation during flight. These activities also have a strong impact on several terrestrial applications including electronic components of irradiated instruments, telecommunications and navigation devices, radiation protection systems for occupational exposure and nuclear power plant incidents, weather forecasting, nuclear medicine and radiation therapy of cancers with emphasis on hadron therapy.

RECOMMENDATIONS

RADIATION DOSIMETRY RECOMMENDATION 1:
Research activities in the domain of space radiation dosimetry have matured gradually and have had major achievements involving a broad international scientific community, with Europe as a major leader. Future efforts should focus on the development of passive and active shielding materials together for temporary shelters necessary for lowering radiation risk to humans, particularly for long-duration exploration missions and extravehicular activities. This also concerns the development of individual detectors and real-time detection of radiation components that should involve real-time calibration for a better assessment of dose exposure. This would require implementation of additional instruments on board the ISS and access to ground-based ion accelerator facilities provided by ESA at GSI. Also, additional efforts have to be made for better forecasting of solar events and the development of improved transport codes and radiation modelling.

RADIATION DOSIMETRY RECOMMENDATION 2:
A more integrated approach should be taken that includes and strengthens cooperation with the radiation biology community, allowing a better delineation of the biological effectiveness of radiation and individual dose in inner organs.

4. Physical Sciences

4.1 Overarching Recommendations for the Physical Sciences Programme

In general, microgravity conditions, particularly over long time scales, are of great potential interest to physical sciences experiments. In many cases, gravity has a disturbing impact on the system under study, and cannot be evaded on the ground. Many research groups are competing for flight opportunities, and the experiments being proposed are widespread over many fields of research. While there were several recommendations for potential improvement identified for many projects and which are appropriately detailed in the subsections of this part of the report, we shall here list a few overarching issues which were encountered frequently enough to merit particular emphasis .

OVERARCHING PHYSICAL SCIENCES RECOMMENDATION 1:

In many projects, the justification for performing experiments in microgravity was not entirely convincing or was even poor. In particular, before experiments involving 'model systems' are funded, possible alternative routes to answering the scientific questions posed, such as computer simulation or ground-based model systems, should be examined with scrutiny.

OVERARCHING PHYSICAL SCIENCES RECOMMENDATION 2:

In several projects, it was not entirely clear how space-borne research related to ground-based research, and why the former would be so indispensable to the latter. The need for (many) preparatory ground experiments must be justified in future proposals and activities. In particular, wherever the term 'model system' is being used, we strongly encourage a closer look at what is being proposed as a model for what, and to consider the well-developed possibilities of doing numerical simulations instead.

OVERARCHING PHYSICAL SCIENCES RECOMMENDATION 3:

Wherever industrial applications are put forward as a justification for microgravity research projects, it should be made very clear and explicit exactly what application is expected to benefit from the results, in what respect, and in what time frame. There should be a proven industrial interest of the very experiment under consideration in order to underpin the relevance of the application. The best and most obvious way for industry to prove such interest is by providing a substantial financial contribution to project funding.

OVERARCHING PHYSICAL SCIENCES RECOMMENDATION 4:

The varying degree of scientific quality of the projects reflects some room for improvement in the review process. In general, it appears that fewer projects should be funded, and given more funds individually.

Notwithstanding the points made above, it should be noted that there are some truly outstanding experiments found in the physical sciences portfolio of ELIPS, and therefore continuation of the ELIPS programme should be given the highest priority.

4.2 Fundamental Physics and Atmospheric Physics

4.2.1 Cold atom sensors and related fundamental physics missions

Many fundamental and compelling questions about the underlying fabric of Nature (e.g. are the constants of Nature really constant? How accurate and complete are our theories of general relativity and gravity? Are we missing mass in our view of the universe?) can only be answered through experiments that require access to the laboratory of space. The following areas have been investigated.

Quantum-atomic sensors

At present, a significant and thriving component of the fundamental physics (FP) programme is centred on the use of quantum sensors based on cold atom interferometry (e.g. atomic clocks, gyroscopes, gravitometers, etc.). Cold atom space experiments exploit access to space in several distinct ways. First, the sensor is operated in a different space–time coordinate frame due to its location in a different gravitational potential from that available on Earth. If the sensor is a clock, such as the clocks in the ACES mission *(Figure 18)*, then by comparison to terrestrial clocks, fantastically accurate measurements, for example, of gravitational red shifts can be made and predictions of Einstein's theory of relativity can be tested. Second, in the absence of the terrestrial-scale acceleration of gravity, the atoms used in the sensors can be observed for far longer times than in an Earth-based laboratory, dramatically improving both the precision and accuracy of the sensor itself, enabling fundamental research, new space-ready technologies and benefits to systems on Earth.

To date work in this component of the ELIPS portfolio is of excellent quality. It has been productive, resulting in highly regarded papers published in leading scientific and technical journals. Beyond the impact of generating fundamental knowledge, many of these projects have significant impact potential for both space exploration and for humankind on Earth. For example, the atom interferometers have relevance to gravimetry and geodesy, the atomic clocks have relevance to GPS and global time coordination and synchronisation. Research in FP also produces economic benefit via spin-off technologies as exemplified by the formation of the start-up company MuQuans.

Consistently the argument for access to space is compelling – the research goals cannot be

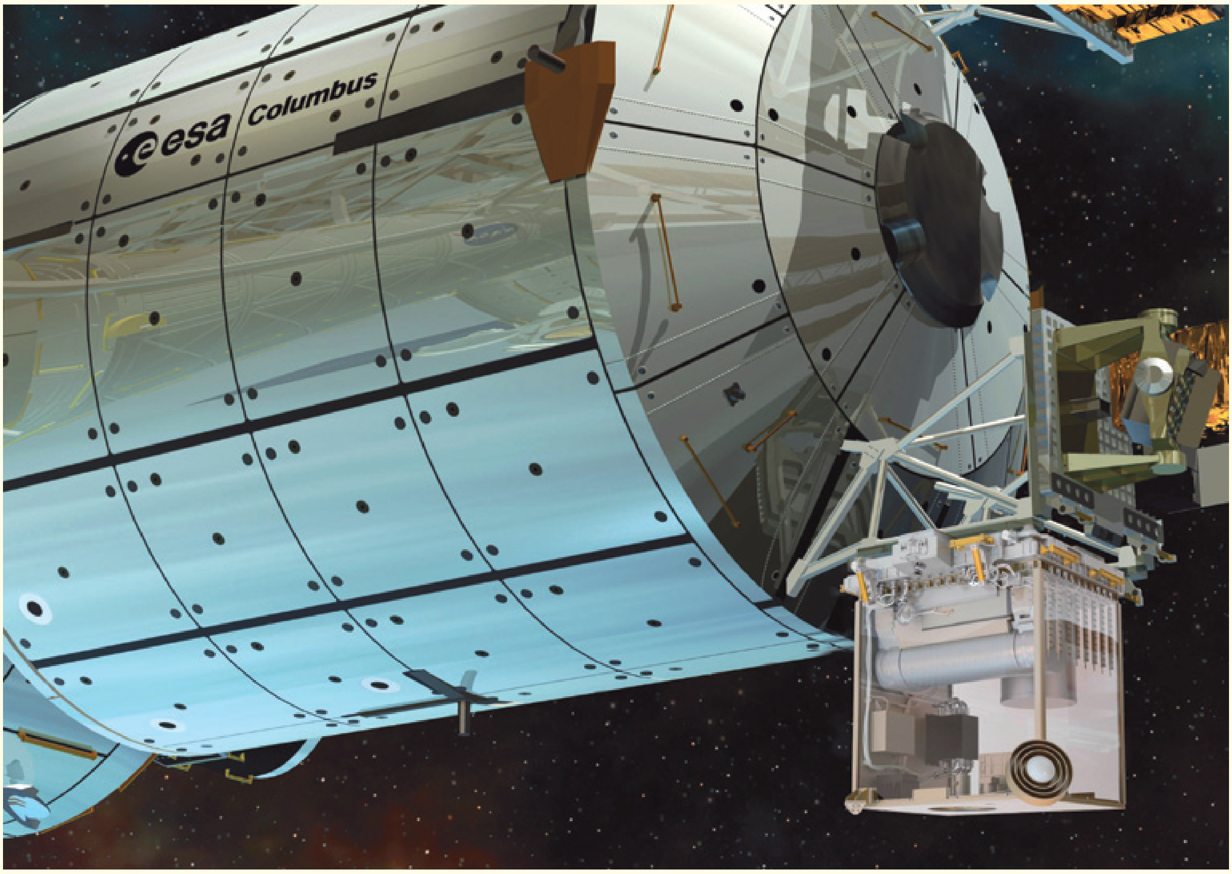


Figure 18: The ACES (Atomic Clock Ensemble in Space) is a fundamental physics experiment based on a new generation of atomic clocks operated on the ISS. The ACES payload is attached to the Columbus Lab (Credit: ESA)

accomplished without it. In addition, important components of research supported in the European programme (e.g. QUANTUS, ICE, etc.) have made broad use of European low gravity facilities such as drop towers and parabolic flight aircraft, activities that not only generate fundamental results, but are also particularly effective in proof-of-principle testing and hardware development.

Ultra high-energy cosmic rays

One hundred years after the discovery of cosmic rays, the study of charged cosmic radiation remains a vital activity in FP. One of the most fascinating aspects is the understanding of the high-energy cosmic ray spectrum and its composition. Cosmic ray flux falls steeply with energy and at the highest energy scale (10^{18} eV or more) it is necessary to use the Earth's atmosphere as a "converter" and to detect the cosmic ray cascades created at high altitudes. Signatures of these cascades have been observed using the large telescope in the Pierre Auger observatory in Argentina to measure particles and fluorescence from the ground. These observations have revealed an important feature identified with the GZK cut-off. This cut-off is related to the interaction of cosmic ray protons with the cosmic microwave background, issues of significant importance to theories of quantum gravity and physics at the Planck scale. Unfortunately, the cut-off is just at the sensitivity limit for terrestrial observation.

In order to extend these measurements, observation from space is the next step. The volume of the atmosphere which can be monitored from space is about two orders of magnitude larger than from the ground, allowing observations to be extended to the highest energy range. This is the motivation of the JEM-EUSO experiment. JEM-EUSO is a large volume experiment, of the class of the AMS-02 magnetic spectrometer: such experiments are examples of a particularly effective utilisation of ISS as a laboratory for astrophysics and for particle physics observatories.

RECOMMENDATIONS

COLD ATOM SENSORS AND RELATED FUNDAMENTAL PHYSICS MISSIONS RECOMMENDATION 1:

To best meet the mission goals of ACES, ESA should engage the participation of as many precision time-keeping laboratories worldwide as possible. This in turn will create a unique global time-keeping network with capabilities beyond anything possible without ACES that will have significant terrestrial impact beyond the fundamental science motivation of the project.

COLD ATOM SENSORS AND RELATED FUNDAMENTAL PHYSICS MISSIONS RECOMMENDATION 2:

A long-term strategy for use of atom interferometery and space-clock technology should be developed within ESA, starting with a strategy that reaches across ESA directorates. The planning should also be done in cooperation with other agencies both inside and outside the EU.

COLD ATOM SENSORS AND RELATED FUNDAMENTAL PHYSICS MISSIONS RECOMMENDATION 3:

Fundamental physics of particles at the highest possible energies demands access to space using large observatories. The JEM-EUSO experiment is an excellent example of important progress in this field. ESA should plan projects and collaborations to retain leadership at this frontier. It should continue to support this project for possible deployment by the second half of this decade.

COLD ATOM SENSORS AND RELATED FUNDAMENTAL PHYSICS MISSIONS RECOMMENDATION 4:

Fundamental physics experiments in general are very technologically demanding and require significant R&D investment. The SOC project is an excellent example. It is imperative that R&D investment be coordinated between ESA fundamental physics projects, between various funding sources outside of ESA, and in cooperation with industry. This will not only increase efficiency and flight readiness, but it will foster technological spin-offs and increase the potential economic impact of space flight.

4.2.2 Atmosphere observations

Environmental physics, covering the research area of atmosphere–space interactions (in particular, the ASIM project), was identified as one of three major fields of interest in fundamental physics research during the last ELIPS review. This review also encompasses the ICAPS project given its relevance to environment and climate physics. Both ASIM and ICAPS have undergone significant development to date, although their respective missions have yet to be flown. The ASIM fit, due to lack of mobilisation of funds, had to be cut back; nevertheless, the reduced fit still offers an excellent opportunity to advance atmosphere–space and thunderstorm research and provides unprecedented spatial coverage of related phenomena. ASIM does not specifically require microgravity conditions, but benefits from low orbit and high spatial and temporal coverage.

ASIM benefits from the ISS's low orbit, giving it the ability to conduct high resolution atmospheric observations in comparison to polar orbiting or geostationary satellites. As a second and equally important benefit, the low orbit provides very high spatial resolution. Although separate from ESA's climate AO, the ASIM will be a good demonstration of the ISS's Earth observation capabilities.

Convective clouds, manifesting themselves into thunderstorm clouds, are driven by surface convection and atmospheric stability, both of which can be influenced by atmospheric aerosol and surface air pollution. The ASIM programme can provide top-of-atmosphere observations to complement ground-based and in-situ observations underpinning aerosol–cloud–precipitation–climate interactions as well as advancing our basic understanding of charge and electrical currents in the atmosphere. In addition, lightning or electrical discharges in the atmosphere are a source of NOx, which is a greenhouse gas. ASIM will provide a high spatial resolution database on upper atmosphere NOx sources and distribution.

The ASIM fit seems to have been finalised albeit at a reduced capacity that should still be sufficient to meet most of the original objectives. The reporting on scientific progress within ELIPS is unclear. Many scientific publications are presented as scientific outputs although few, if any, acknowledge ESA–ELIPS.

The ICAPS science project has been developing and testing instrument components in laboratory and non-space zero-gravity conditions. The proposed multipurpose experimental chamber offers extensive opportunities for aerosol, dust, and liquid and solid cloud particle research relevant to both cosmic and Earth (climate)-related research topics in the absence of gravity, which significantly alters aerosol dynamics and evolution. However, some of the aerosol-cloud experiments need to be better justified in terms of advancing our knowledge of the climate system on (a gravity-driven) Earth system.

The aerosol-cloud component of ICAPS is potentially relevant to Earth-based research in that aerosol haze and cloud layers play a vital role in greenhouse gas-induced global warming along with contributing to a dichotomous effect on precipitation, leading to flooding under certain scenarios and drought under other scenarios.

The ICAPS instrument seems to be behind schedule, despite having made good progress in sub-component instrument development. The experimental challenges, particularly those relating to cloud droplet and ice particle nucleation, are immense as are those relating to generating known and quantitative samples of internally mixed anthropogenic aerosols. There appears to have been very good progress on the aerosol injection system. Again, many scientific publications are presented as scientific outputs although few, if any, acknowledge ESA–ELIPS. The ELIPS contribution, even if not directly financial, should be acknowledged.

ICAPS requires zero-gravity conditions to conduct sufficiently long experiments relevant to both cosmic dust agglomeration and aerosol coagulation, along with experiments on cloud droplet activation, ice particle nucleation and the life cycle of these particles in clouds. Gravity provides one of the major influences on particle removal, with removal rates rapidly increasing for large agglomerates, thus perturbing the quantification of cosmic dust evolution under zero-*g* conditions. The cosmic dust agglomeration component of ICAPS is most relevant to space processes and space research.

RECOMMENDATIONS

ATMOSPHERE OBSERVATIONS RECOMMENDATION 1:

The planned programmes should be completed. Further delays in experimental development severely hamper the advancement of scientific research objectives and should be avoided. Given the development time that has elapsed, the programmes could potentially benefit from a review of specific scientific objectives to evaluate which of the experiments need to be fine-tuned or updated, while not altering the installation development.

ATMOSPHERE OBSERVATIONS RECOMMENDATION 2:

While there is broad relevance to Earth-based research in the ICAPS programme, the direct link, particularly in terms of practical translation of the space-borne research, needs to be better elaborated and justified.

ATMOSPHERE OBSERVATIONS RECOMMENDATION 3:

Dissemination of results needs to be improved. ESA and/or ELIPS should be clearly acknowledged wherever involved.

4.2.3 **Soft matter**

The projects labelled "soft matter" deal with grains in space, colloidal solutions, and well defined "dust" particles in plasmas.

Space grains and the SODI colloid experiment

Deep insight into the collective behaviour of grains in zero gravity is essential for understanding the formation of planetesimals and accretion discs. Under these conditions, the impact behaviour of ensembles of dust particles, which also plays a substantial role in many settings on ground, can be investigated without disturbing side effects due to gravity. Clustering and phase transitions in granular fluids can be studied without sedimentation. Specific differences between granular gases and real gases have already been successfully analysed. Similarly, sedimentation and convection in colloidal suspensions *(Figure 19)* have a strong impact on aggregation and crystallisation processes. If the latter are to be studied in detail, these side effects must be avoided.

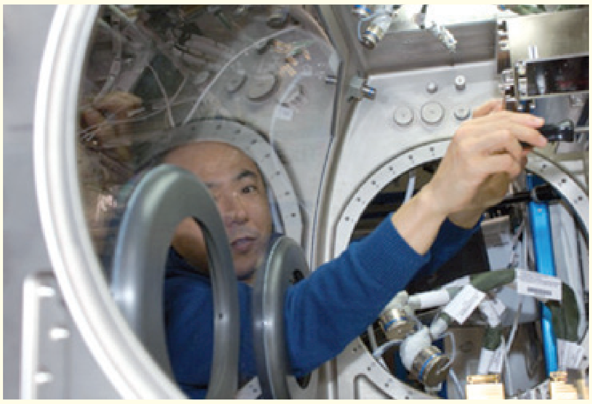


Figure 19: Japanese astronaut Satoshi Furukawa installing the SODI-Colloid experiment into the Microgravity Science Glovebox (Credit: ESA/NASA)

Complex plasmas

Charged micrometre-sized particles, which are directly observable with visible light, float in dilute gaseous plasma, whereas they would settle without microgravity conditions. Experimental observations obtained so far on ISS include gas–liquid phase separation and the formation of a string phase in the presence of applied alternating electric fields. This allows the analysis of processes similar to those occurring in electro-rheological fluids. More complex spatial structures like sheets are expected in future experiments.

Common to all of these experiments is the study of the dynamics of particles of micrometre size which differs drastically or is even arrested in the gravitational field on Earth. Parabolic flights and experiments on the ISS are essential to answer the relevant scientific questions posed in the different sections of the soft matter ELIPS research programme. Publications presented so far are

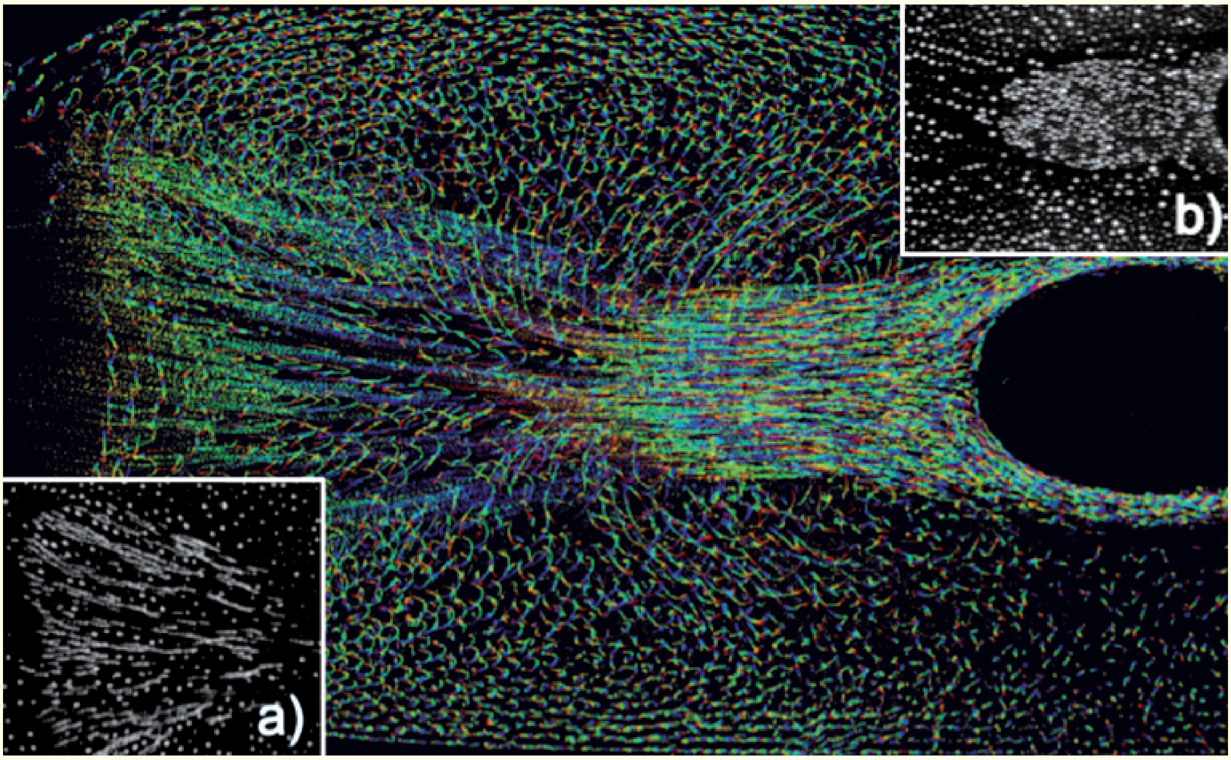


Figure 20: Generic processes observed in complex plasmas with the PK-3 Plus laboratory on the International Space Station ISS. The figure shows trajectories (colour coded) of particles penetrating from the left side into a stable cloud of bigger particles, first leading to lane formation (see insert a) from Sütterlin et al., Phys. Rev. Lett. 102, 085003 (2009)) and later to phase separation (see insert b) from Ivlev et al., Europhysics Letters 85, 4 (2009))

rated from good to excellent. Based on the experience gained and on previous results obtained, the goals set in the proposals for the coming period can be reached. It should also be noted that there has been significant spin-off, resulting in a novel plasma healthcare concept which resulted from the cold plasma studies.

The argument for access to zero gravity is thus compelling for both types of systems – space grains and complex plasmas – if the unwanted side effects cannot be avoided by other means. For space grains, it is clear that buoyancy matching is not feasible. Furthermore, the experiments cannot be replaced with computer simulations, as some important aspects, in particular for irregularly shaped grains, are difficult (if not impossible) to simulate with sufficient accuracy and particle number. However, when considering the use of complex plasmas in microgravity as model systems for microscopic transport phenomena in condensed matter, comparisons with computer simulation as a potentially high-performing and more economical alternative should be performed in order to assess its relevance. The latter may not apply for more complex phenomena in plasmas, which are interesting to be studied for themselves.

For colloid suspension experiments, care must be taken to make sure buoyancy matching is not a viable alternative for answering the scientific questions asked.

RECOMMENDATIONS

SOFT MATTER RECOMMENDATION 1:
Studies of systems containing particles of micrometre size and larger should be continued under microgravity conditions. The results are of potential importance for the broader physics community.

SOFT MATTER RECOMMENDATION 2:
In the experiments devoted to electro-rheological plasmas, more complex spatial structures should be looked for, and the possibility of inducing shear flow should be examined.

SOFT MATTER RECOMMENDATION 3:
Great care should be taken that only those scientific questions are posed (and corresponding experiments flown) which cannot be answered by means of ground-based experiments or computer simulation. The latter applies specifically if so-called model systems are being investigated.

4.3 Fluid Physics

4.3.1 Fluid dynamics

Fluids are ubiquitous in nature, technology and everyday experience. The understanding of transport properties in liquids and their mixtures has important industrial and technological applications, for example in oil recovery, crystal growth, material processing, and so forth. In order to make accurate predictions of these physical phenomena, it is necessary to have precise knowledge of their transport coefficients and, more generally, to understand the hydrodynamic behaviour of these systems under microgravity conditions where buoyancy, sedimentation and convection are absent. Transport coefficients have been measured only under Earth conditions, where convection can be the dominant effect.

The ISS makes possible, thanks to the elimination of secondary flows and instabilities caused by gravitational convection, a better experimental study of numerous hydrodynamic processes such as free-surface flows, dynamics in multicomponent, multiphase and especially heterogeneous media, phase transition processes (crystallisation, boiling, condensation), and influence of flows on chemical reactions, including combustion. If one would like to eliminate sedimentation and buoyancy effects on Earth, one would have to make the system much smaller (e.g. thermo-capillary flow scales with length while buoyant convection scales with length). But such miniaturisation necessitates an increased effort in measurement technology (temporal and spatial resolution). Moreover, scale-down would restrict the investigations to certain regions of parameter space. One advantage of microgravity is the possibility of enlargement which enables, in many cases, better measurement of the phenomena in question.

When measuring transport properties on the ISS one needs to exercise special care because the benefits of the microgravity environment can be altered by the vibrations of the space station (the so called *g*-jitters). Significant effort has been dedicated by the teams involved in this project to clarify the role of these on-board perturbations, either by numerical simulations prior to the flight, or by parabolic flight experiments. Theoretical models have been studied in order to assess the importance of vibration-induced convection.

Other important studies have focused on pattern formation and hydrodynamical instabilities due to the coupling between chemical reactions which may occur at interfaces. These theoretical studies complemented through ground-based and microgravity experiments lead to a quantification of the changes in heat/mass transfer or mixing rates. Finally, vesicles, capsules and red blood cells under flow are a subject of considerable interest. Understanding their motion and dynamics is essential both at the fundamental level as a branch of biocomplex fluids, and at the technological level, in the context of areas such as lab-on-chip technologies, targeted drug delivery, and blood flow diseases. The overall quality of publications is very good.

Microgravity is an issue of major importance because of its implications for human blood circulation during long stays in space (experiments conducted in parabolic flights show that 20s of microgravity are not sufficient for the human vascular system to reach steady state conditions).

RECOMMENDATIONS

FLUID DYNAMICS RECOMMENDATION 1:
Experiments would greatly benefit from improved downloading and zipping capabilities on the ISS. As a general remark, there should be better synchronisation and a shorter time lapse between the timing of AOs and missions.

FLUID DYNAMICS RECOMMENDATION 2:
From the technical point of view, vibration devices for fluids with a large range of amplitude and frequencies and good temperature control are required.

FLUID DYNAMICS RECOMMENDATION 3:
Whenever relevant to the problem at hand, theoreticians should consider extending their techniques, which are so far essentially based on partial differential equations such as Navier-Stokes, diffusion equations, etc., to other methods where one can model several processes at a more fundamental level. These methods include lattice Boltzmann simulations, dissipative particle dynamics, and stochastic rotation dynamics. The advantage of these models over macroscopic models is the representation of the interfaces which are not sharp but diffuse.

4.3.2 Phase change and heat transfer

The general objective of this disciplinary research topic is to gain understanding (and to validate theoretical models and benchmark numerical codes) about heat and mass transfer processes in fluids. This area of research has significant application relevance when considering heat transfer devices for ground and space applications (cooling of electronics and engines, power plants heat exchangers, etc.). The ELIPS programme and the ISS Boiling Experiment Facility *(Figure 21)* are central in this context and enable the scientific community to perform challenging studies into the complexities involved in bubble formation as a result of heat transfer: What about the variations in the properties of the heating surface? What roles do surface tension and evaporation play during nucleate boiling

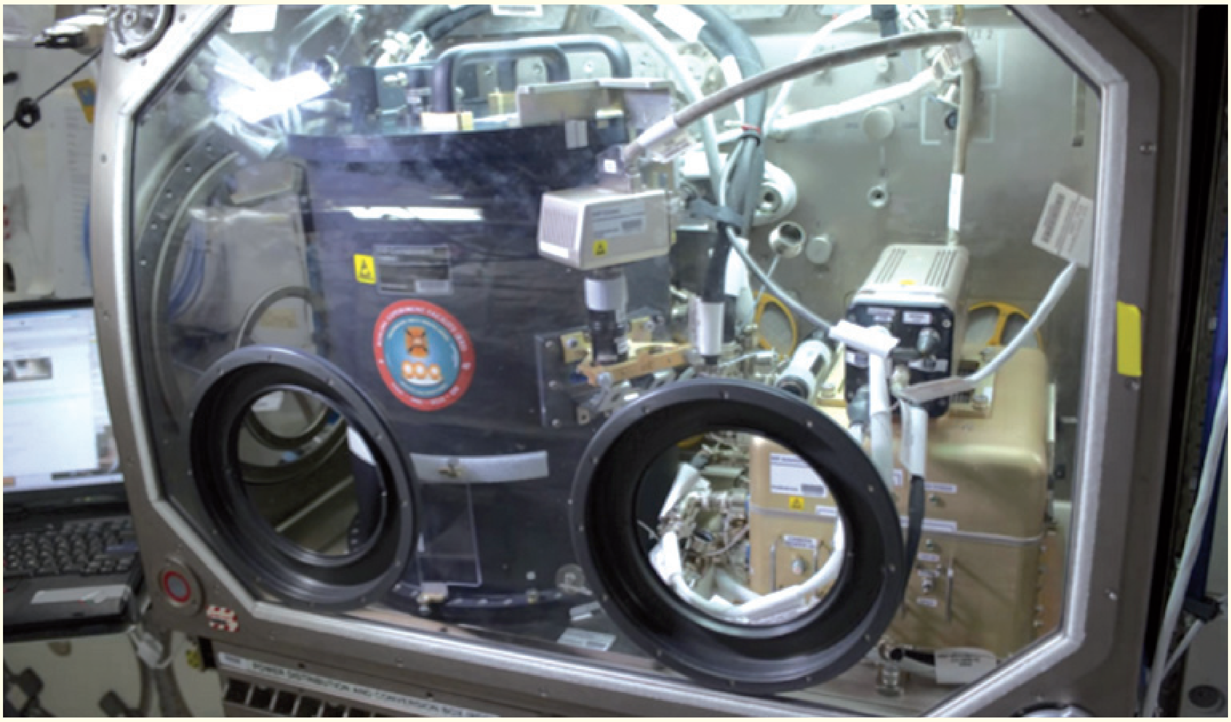


Figure 21: The boiling experiment facility installed inside the microgravity science glovebox on-board the ISS (Credit: NASA)

when buoyancy and convection are not in the equation? A major obstacle to tackling these questions by means of computers is the fact that the systems of interest are far from thermal equilibrium. Several key aspects, such as the problem of moving liquid contact lines, are not understood even on a basic level, thus precluding reliable computer simulations.

Areas that have been investigated include:

- Quantitative analysis of surface temperature and velocity fields for surface-tension-driven instability, without any influence of buoyancy.
- Investigation of the occurrence of purely surface-tension-driven interfacial turbulence in evaporating liquid layers, without any influence of buoyancy.
- Improved knowledge of heat and mass transfer around an isolated bubble in pool boiling, including the micro-region near the contact line.
- Investigation of the important effects of an electrostatic field in pool boiling heat transfer, which affects heat transfer coefficients in microgravity.
- Demonstration of the enhanced performance of advanced capillary structures (microgrooves orthogonal to main grooves) for heat pipes and correlation of heat transfer coefficient with 3-phase contact line length.
- Visualisations of the dynamics of boiling crisis (dry-out) near the liquid–vapour critical point under magnetic gravity compensation.

By controlling for gravity while on the ISS scientists can investigate separately the various elementary processes of boiling, thus providing deeper insights on a fundamental science level. Improved efficiency in cooling technology has the potential to lead to positive impacts on the global economy and environment. The determination of many aspects of boiling is far too complex to rely on theory and numerical simulation. Some microgravity experiments are thus necessary.

RECOMMENDATIONS

PHASE CHANGE AND HEAT TRANSFER RECOMMENDATION 1:

Results and data obtained in the context of ELIPS should be better disseminated and made available to the scientific community, acknowledging ESA and ELIPS wherever appropriate and by publishing in journals with high impact factor.

PHASE CHANGE AND HEAT TRANSFER RECOMMENDATION 2:

The research effort should focus on specific phenomena where the elimination of buoyancy and convection is really crucial.

PHASE CHANGE AND HEAT TRANSFER RECOMMENDATION 3:

Access to microgravity and ISS experiment facilities should be maintained, as far as it is scientifically well justified.

4.3.3 Complex fluids

Complex fluids may be defined as soft materials, the microscopic constituents of which are already rather complex by themselves, be it the chain-like molecules of a polymer melt, the surfactant-laden bubbles of foam or froth, the charged polymer spheres and poly-ions of a colloidal suspension, or the liquid droplets in an emulsion. Since these systems are much more significant to everyday life than simple fluids, a deep understanding of the static and dynamic properties of complex fluids is of utmost importance for a vast number of industrial applications.

Due to the mere size of the constituents of complex fluids, gravity matters considerably more for complex fluids than for conventional materials. Colloidal suspensions as well as emulsions tend to phase-separate under gravity unless great care is taken to prevent sedimentation. It is therefore unsurprising that complex fluids have always been in the first row when applying for microgravity research opportunities. Although in many cases one can circumvent gravity effects by appropriate buoyancy matching, suitable surfactants, and osmotic stabilisation, there are some cases where this is not readily possible, and microgravity experiments appear instrumental, if not inevitable, for deepening physical insight into the matter.

It should also be mentioned that most complex fluids of interest are far too complex to rely on computer simulations. The two main obstacles here are the many coupled molecular-scale transport processes (surfactant diffusion in several media and along surfaces, exchange between micelles and solute, micellar diffusion, etc.) and the coupling of flow and advection to moving liquid interfaces. There remains thus a considerable number of fundamental open questions which can be successfully tackled neither by ground-based experiments nor by computer simulations. Complex fluids research in general will therefore remain eager for microgravity research opportunities for many years to come.

A review of past activities within the ELIPS programme, as detailed during the Noordwijk workshop, identified two key issues which appear very promising for a continued microgravity research effort along the quite successful lines pursued so far:

a) It could be shown that under microgravity foams consisting of pure water as the fluid phase could be generated and stabilised. This important (and at first glance counter-intuitive) finding opens up the possibility to study processes like foam drainage in the absence of interface elasticity, coupling to surfactant flow fields, and with purely Newtonian fluids involved.
b) Homogeneous metal foams could be created, and the effect of the additives on drainage and coalescence could be studied with unprecedented success. The role of the blowing agent for foam breakdown could be clearly assessed.

There is no way to conduct similar studies on foams in ground-based experiments, as buoyancy matching is impossible for foams. While some geometry-related questions regarding foams may be investigated using emulsions instead, most dynamic properties are strongly affected by the replacement of the (compressible) gas with an (incompressible) liquid, not even mentioning the impact on surfactant transport and interface rheology. For metal foams, emulsion-based model systems are entirely impossible.

RECOMMENDATIONS

COMPLEX FLUIDS RECOMMENDATION 1:
It is recommended that within the complex fluids projects, priority is given to fundamental research on foam systems, in particular on dynamics of purely aqueous foams and on the physics of metal foams and the role of additives therein. These projects are furthermore expected to fertilise each other. Since metal foams are among the super-materials of the future and still bear an enormous potential for process innovations, this research should be given high priority in the complex matter space research community.

COMPLEX FLUIDS RECOMMENDATION 2:
It is recommended that only the high scientific quality projects be considered for funding, in order to promote high level publication. In this context, a critical eye on the necessity of microgravity will be important.

4.4 Metallurgy and Crystallisation

The relevance of space-research or microgravity research in the field of metallurgy and crystallisation essentially lies in the possibility of studying liquid or solidifying molten metals, metallic alloys and semiconductors in the absence of convection and hydrostatic pressure. This allows for thorough investigations of diffusion and surface-tension-driven solidification phenomena. Similarly, protein crystallisation from solutions and the first stages of zeolite aggregation may conveniently be studied. The higher purity and lack of convection in the microgravity environment are essential in order to understand nucleation and transport phenomena.

In the case of liquid metals and alloys there are two areas where low gravity research is able to make significant contributions to our understanding. These are: (i) *Containerless melting and processing,* where very reactive alloys can be melted under conditions where they are not contaminated by contact with the furnace walls. Contamination is reduced on Earth by using water-cooled induction furnaces, so that a solid skull separates the reactive molten alloy from the heating device. This leads to a limited amount of superheat and thus to problems in filling castings. (ii) *Measurements of fundamental properties* such as surface tension and wettability, where the shape adopted by the liquid metal is not influenced by gravity. Data needed to develop models for solidification and casting processes can thus be obtained.

The areas where metallurgical and crystallisation research has been carried out in the ELIPS frame can be grouped under four headings, which will be covered in turn: (i) crystal growth, (ii) directional solidification, (iii) out-of-equilibrium solidification, (iv) thermophysical properties. Although in the following a separate description of these four areas is provided, it should be noted that they are strongly correlated and overlap significantly. This is in particular true for the areas (i)–(iii) as all crystallisation and solidification phenomena by nature may occur only out of equilibrium. The distance from equilibrium of the systems under investigation actually sets the border of the areas. It is evident, however, that some coordination and integration between the experiments pertaining to areas (ii), (iii) and (iv) would ultimately be beneficial to both communities.

Crystal growth

In the case of molecular crystals (such as proteins), growth experiments in microgravity have highlighted two main differences with respect to ground experiments: first, crystal nucleation seems to take place in two steps and, second, the transport

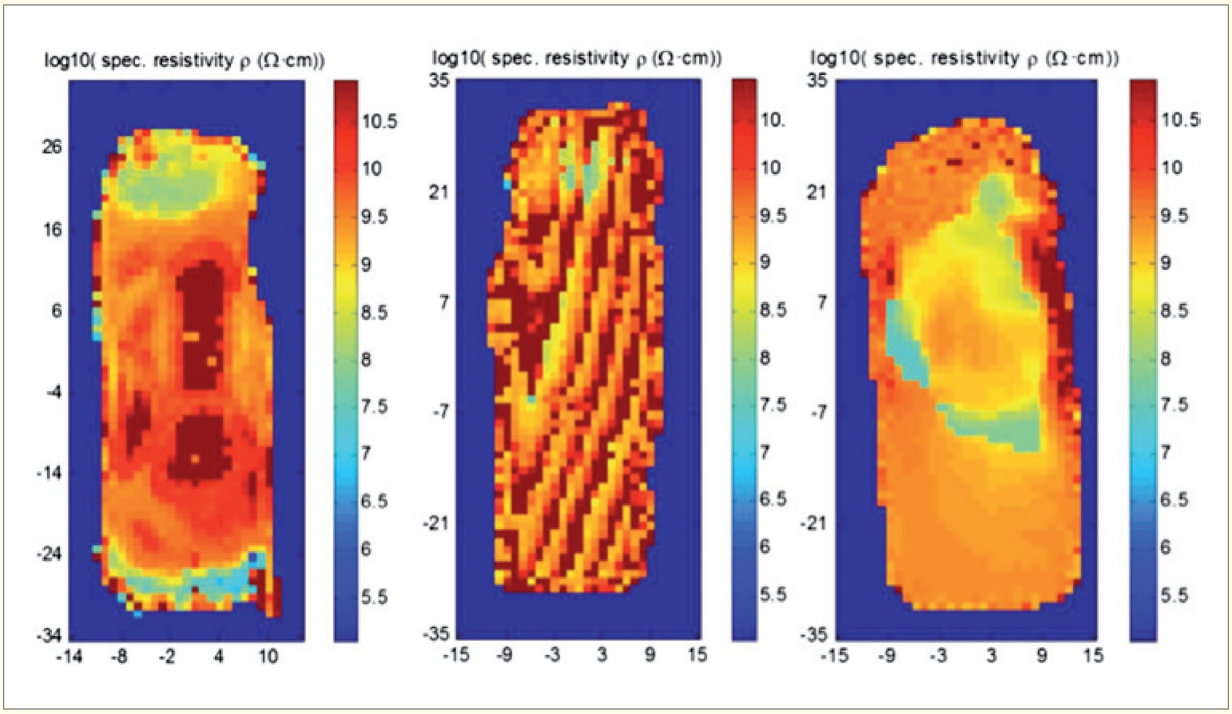


Figure 22: Resistivity maps of bulk (25mm diameter) CdTe crystals. The two crystals grown in space (left, Foton M3 satellite mission) have a higher and more uniform distribution than the crystal grown on the Earth (right) (Credit: Michael Fiederle)

mechanisms in the absence of convection lead to formation of a zone depleted of impurities around the growing crystal. Crystals of higher perfection can be obtained in this way, which in turn allows very accurate crystallographic studies and protein structure identification, showing the direction for ground-based processes to seek to emulate diffusive conditions. Space experiments were indeed essential to the understanding of the transport mechanisms that control macromolecular crystal nucleation and growth. They paved the way to ground-based processes which aim at emulating the diffusive conditions of the space environment. The fallout effects of the space experiments are numerous, both from a theoretical and a practical standpoint, so that the experiments may now successfully be pursued on the ground. In the case of zeolites, experiments suggested that gravity plays a big role in the initial self-organisation of the building blocks. However, the experimental observations are so far insufficient to draw sound conclusions and further work on board ISS is requested in order to have a reliable description of zeolite crystallisation and to develop a technological path for controlling structure and morphology of the crystals. The activity on semiconductor crystal growth essentially followed two directions: investigation of dewetting effects during directional crystallisation of compound semiconductors, and formation of precipitates (and their incorporation) during directional crystallisation of multi-crystalline silicon. Dewetting phenomena were first observed in space-grown crystals more than 15 years ago and are here exploited to improve the crystallographic quality of technologically important crystals (for instance CdZnTe and GeSi). The growth of multicrystalline Si in space has not been attempted so far due to the high melting temperature (>1400 °C), exceeding the capability of current ISS facilities. It has to be stressed that neither dewetting experiments nor crystallisation of MC-silicon are expected to provide new fundamental knowledge. The ELIPS crystal growth research is altogether of a high scientific profile and has so far produced a good number of high-quality papers. It is however necessary to differentiate between the projects: whilst in the case of proteins the most significant work was to a large extent based on space experiments, the semiconductor activity, although of a high level, was essentially based on ground experiments. Furthermore the project on proteins also resulted in a new crystallisation facility which was successfully tested in microgravity and is now used for ground experiments. As already mentioned above, it is expected that this method will facilitate future work in structural biology.

Directional solidification (close to equilibrium)

The reported activity is mostly based on ground experiments so far. A new series of microgravity experiments is planned to begin during 2012. The highlights in this area include a deeper understanding of dendrite formation *(Figure 23)* and coarsening, of the columnar-to-equiaxed transition,

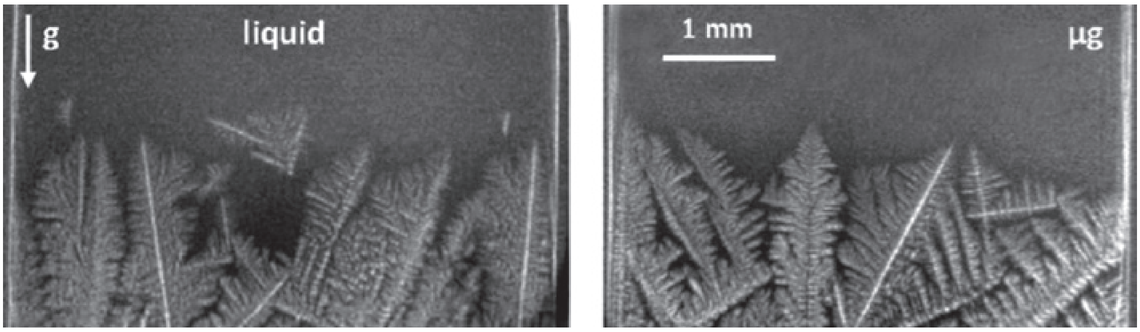


Figure 23: Floating of dendrite fragments due to buoyancy, frequent in upward solidification on earth, is suppressed in microgravity. First in situ observation by X-ray radiography imaging during MAXUS12 sounding rocket flight (13/02/2012) of dendritic growth under diffusion transport in a metallic system. Al – 20 wt% Cu alloy cooled down at 0.15 °C/s under applied thermal gradient G = 15 °C/mm (measured growth velocity V = 16 µm/s). (Courtesy of : H. Nguyen-Thi, XRMON Team)

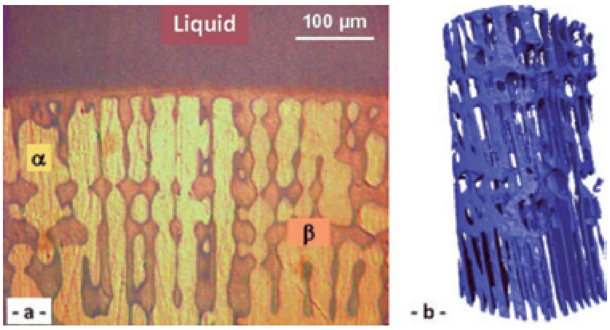


Figure 24:
a) Longitudinal section showing cooperative growth of a and b lamellae “across peritectic temperature” (b ahead) in Cu-21 wt% Sn alloy solidified at V = 0.58 µm/s in a capillary tube.
b) Tomography at TOMCAT synchrotron beamline shows a single a grain.Microgravity experiments under diffusion in bulk samples are under preparation. (Courtesy M. Rappaz, METCOMP Team)

the observation of orientation-dependent laminar structures in binary and ternary alloys, and the validation/benchmarking of advanced modelling and numerical simulation. Future research will aim at a deeper understanding of pattern/microstructure formation in alloys solidified at different rates in the absence of natural convection. This should ultimately help to develop solidification processes for improved alloys. As in the case of semiconductors, there is a need in this area to increase the range of temperatures up to 1500 °C in order to investigate key materials such as nickel superalloys, TiAl alloys and eventually composites. A further point consists in applying external fields (typically magnetic fields) to control/drive the melt convection. In this way, it may become possible to establish a correlation between the microstructure of the solidified alloys and the fluid motion. This should help to develop advanced terrestrial solidification processes. As already noted for the crystal growth section, in the case of directional solidification the scientific output is of a very high level but it has to be essentially ascribed to “preparatory” ground experiments. As also pointed out by the presenter, only a few publications deal with truly microgravity experiments. New X-ray apparatus, allowing in-situ real-time monitoring of solidification processing, was developed in parallel. Although not readily implementable in space experiments on the ISS, this is an important side accomplishment of the ELIPS activity on directional solidification.

Out-of-equilibrium solidification

It is well-established that a wide range of structures can be obtained from the slow cooling rates found in large ingots (where the different solubilities of components in the various liquid and solid phases lead to a range of cooling-rate-dependent structures) to the rapid cooling rates where homogeneous amorphous solids can be formed. Work carried out under microgravity (or reduced gravity) has shown that the extent of undercooling, grain-refinement, and phase selection during solidification are strongly influenced by gravity-driven convection. Similarly, dendrite growth velocity is also influenced by convection under gravity. Hence this research has given significant insight into the role that gravity is playing in influencing the microstructures formed during solidification under a range of cooling rates. The fact that gravity-driven segregation is eliminated has also allowed uniform dispersion of phases – especially enabling minority phases to be obtained. Further work on dendrite growth in undercooled Al-rich Al–Ni alloys, is planned in order to clarify the origin of anomalous growth and permit verification of models of solids from liquids so that the influence of gravity on undercooling is isolated.

Thermophysical properties

As noted above, containerless melting allows some fundamental properties to be measured. Measurements of density and surface tension in Ni-based superalloys, steels, Ti6Al4V, Ti-aluminides, bronzes, Si–Ge have been carried out in parabolic flights or sounding rockets. Measurements showing a scatter of less than 1% were obtained from different parabolic flights. Viscosity measurements showing scatter of between about 12% and 25% have also been obtained for Fe, Cu and Ni. Relevant modelling has been carried out and has allowed improved modelling of tilt-casting of Ti aluminides with reasonable values of viscosity as noted below. The extent of demixing in Cu–Co alloys has also been measured and is planned to be measured in ISS. Ground-based work on solidification of Al-based alloys has been carried out and further work is required under microgravity before this can be quantified and modelled and used in software to model the microstructure of cast alloys. Future work involving more precise containerless measurements of viscosity, surface tension, liquid–liquid interfacial energies, specific heat, and thermal/electrical conductivities in ISS is planned, as is development of a model for liquid demixing and droplet growth in the liquid state.

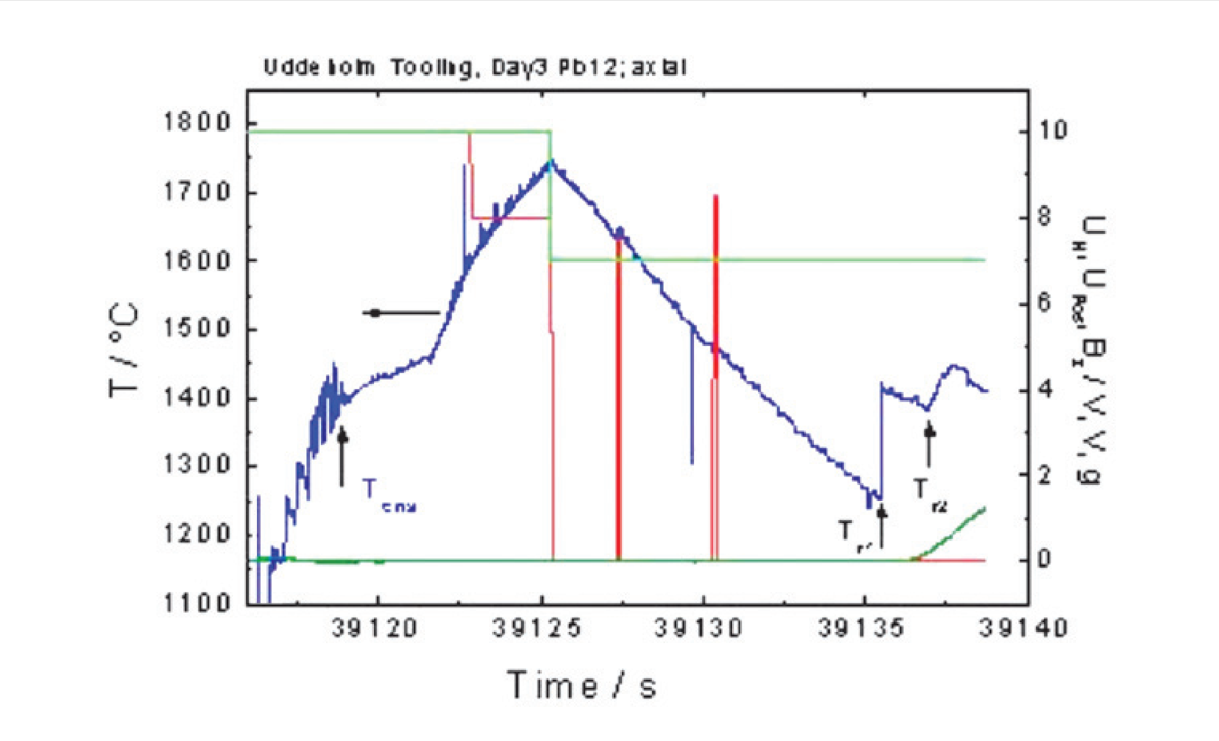


Figure 25: Temperature and fields during levitation of a steel drop (Courtesy of Dr. R. Wunderlich, Ulm)

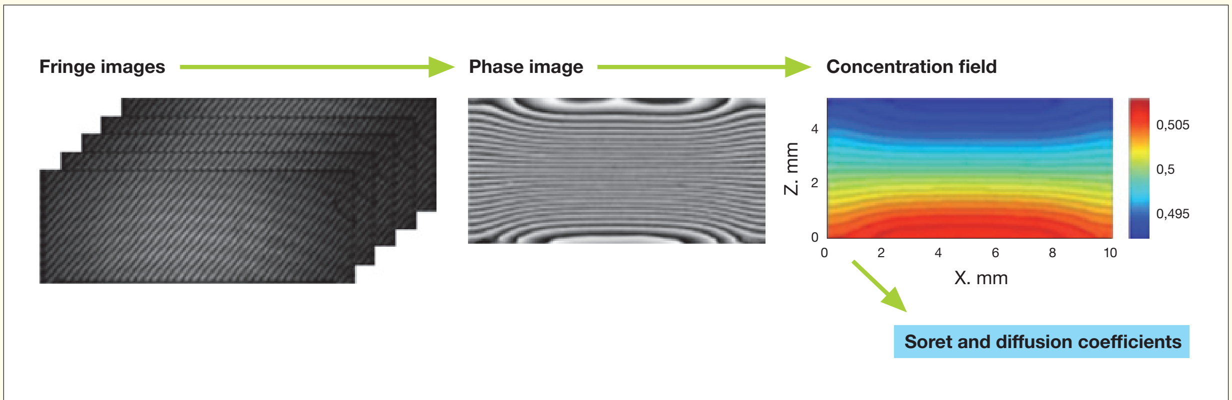


Figure 26: Concentration fields determination for thermodiffusion (Courtesy of Prof. V Shevtsova, Brussels)

RECOMMENDATIONS

Modern theories of crystal growth, crystallisation and solidification are well consolidated. Early crystallisation experiments in microgravity substantially contributed to the understanding of basic phenomena and to the development of a sound theoretical basis. The experiments of the last few years, including those carried out within the last ELIPS programme, did not however provide real breakthroughs nor add substantially new fundamental knowledge. It may be expected that advances in fundamental understanding of crystallisation and solidification processes from microgravity experiments will be quite limited in the future. On the other hand, simulation and numerical modelling are powerful means to predict and investigate the solidification and crystallisation behaviour of different substances. To this extent, precise measurement of physical constants in fluids (viscosity, diffusion coefficients of solutes, surface tension, etc.) are required in order to provide correct inputs for numerical simulation and modelling of solidification processes. This activity makes sense and should be maintained within the ELIPS frame. However, the list of priorities for future experiments should be application-driven and possibly corroborated by a direct industrial involvement. Further, ESA should take the initiative of collecting all results in a database, accessible to the communities of crystal growers and metallurgists, in order to avoid duplication of experiments, secure the widest dissemination of results and support the simulation work with reliable physical parameters.

From the point of view of pure materials development there are very few projects which require microgravity in order to be profitably carried out. In many cases (multicrystalline Si, GeSi, CdZnTe, several alloys, and so on) the costly space experiments are hardly justified by the expected benefits to terrestrial applications (even if those materials are really better when crystallised in space, it is practically not possible to establish space-based production). Consequently ESA should consider the following when reviewing future experiments in the area of materials science/solidification.

METALLURGY AND CRYSTALLISATION RECOMMENDATION 1:

Experiments aimed at obtaining novel materials should have priority over those aimed at improving well-established materials. Alternatively, the companies or entities which can benefit from those advances should bear a significant part of the costs.

METALLURGY AND CRYSTALLISATION RECOMMENDATION 2:

In the case of purely fundamental research, each project should contain a clear statement about the breakthrough in knowledge expected from experiments carried out in microgravity with respect to ground experiments. The high costs of space research are justified only if the expected results considerably add to the body of knowledge in a given field and/or pave the way to a conceptually new field.

METALLURGY AND CRYSTALLISATION RECOMMENDATION 3:

The planned use of existing facilities (furnaces, microscopes, spectrometers etc.), established over decades with substantial investment, cannot be considered to be a sufficient motivation for new projects. The expected scientific output (fundamental knowledge or novel materials) is the only parameter to be considered when judging future projects.

METALLURGY AND CRYSTALLISATION RECOMMENDATION 4:

The number of the expected preparatory ground experiments has to be clearly stated. Normally, the time investment for terrestrial work should be comparable with that required to plan and execute space experiments. Strong deviations from a correct ratio should be foreseen and justified in the proposals. This in order to avoid the word "microgravity" be taken as an alibi for long-lasting ground research.

Perhaps the model which brings the above comments together would be that projects funded to carry out work under microgravity should be ones where data are required for a specific alloy or other material where the potential benefit and application are clearly defined, so that industry is prepared to fund a significant part of the costs. In such a project it is likely that ground-based research would make up a significant part of the programme. In view of the timescales between concept and experiment, this approach would require time being reserved for such experiments in order to fit in with the schedule of ground-based work.

5. Concluding Remarks

The expert committee wholeheartedly agrees that ELIPS hosts a number of exceptional experiments which are of top-level scientific quality and great importance to the scientific community as well to society, and therefore should be continued. To promote the successful development of ELIPS in the future and make it even stronger, the panel reviewed all aspects of the programme including its structure, implementation and scientific merit and came up with a number of recommendations, which have been given throughout this report. The expert committee also made thorough reviews of relevant sub-disciplines in the life and physical sciences with regard to their achievements and space relevance and provided future priorities and specific recommendations for each. In order to optimise the impact of the review process, the concluding messages that the expert committee wishes to convey are summarised in the following points.

1. Industrial interest has to be demonstrated by the industrial actors through the commitment to provide significant (in-kind or financial) support in experiment implementation. For such proposals, the quality of the science, and the extent of industrial support, should be the only two criteria used in assessing whether or not a project is selected. In this context, it is acknowledged that large industrial companies cannot be considered in the same way as small R&D companies and start-ups.
2. In view of the long delays between acceptance of a project and its actual implementation, besides efforts to reduce these delays some periodic re-assessments should be initiated to assess the timeliness of projects.
3. There should be increased publicity of new funding opportunities and AOs, so that new scientists and ideas can be brought into the programme, thus breaking the seemingly closed-loop system.

Following these guidelines and the recommendations outlined in the report will lead to the implementation of scientifically excellent projects with a compelling case for microgravity. Not only should these studies be given ample funds, but great care should be taken to avoid unnecessary delays to ensure the greatest scientific return and overall success. The recommendations outlined in this report should also be considered thoroughly for implementation to ensure that the next phase of ELIPS is as efficient and productive as possible, bringing new discoveries and insights into science in microgravity.

Additionally, the panel noted that not all recommendations made by earlier evaluation exercises (in 2000, 2004 and 2008) were acted upon. With the new approach adopted in this review exercise, some continuity in committee membership in monitoring the programme or in a future evaluation combined with an improved feedback system from ESA should be implemented to address this issue. In addition, the committee will welcome and ask for official feedback on the content of this report.

6. Summary of Findings and Recommendations

The European Science Foundation was commissioned by the European Space Agency to provide an independent scientific evaluation of ESA's ELIPS Programme. This report presents the assessment of the ELIPS programme in terms of its overall structure, programmatic aspects and scientific value, and provides recommendations for the next phase of ELIPS. Additionally, domain-specific reviews and recommendations in life and physical sciences are presented. Overall, ELIPS is recognised as a high-level programme of great scientific value and fundamental to the success of European research in space science. To make a programme of such importance even better, the following recommendations have been developed and represent a consensus among the expert committee members.

6.1 Overarching Programmatic and Structural Issues and Recommendations

6.1.1 ELIPS in the broader scientific landscape

The ELIPS programme is a wide ranging, comprehensive research programme providing research opportunities to scientists across Europe and beyond. It covers many scientific disciplines, spanning human physiology to fundamental physics, and utilises a variety of facilities and platforms. The programme also has a variety of research opportunities, ranging from continuous calls to large-scale dedicated international research announcements. The expert committee wholeheartedly agrees that ELIPS hosts a number of exceptional experiments which are of top-level scientific quality and of great importance to the scientific community as well to society, and therefore should be continued.

OVERARCHING RECOMMENDATION 1:
The ELIPS programme hosts a number of exceptional experiments which are of top-level scientific quality and of great importance to the scientific community as well to society, and therefore should be continued.

Linking Space Research to Mainstream Research Performed on Earth

Exploiting and providing unique experimental conditions, ELIPS has the means to help address numerous contemporary challenges, both scientific and societal. However, it is felt that the ELIPS programme needs to address more of the current key scientific challenges, as recognised by the broader scientific community.

PROGRAMMATIC RECOMMENDATION 1:
It is important to survey which current scientific challenges (going beyond the traditional coverage of ELIPS) could potentially benefit, even marginally, from the conditions and platforms offered by the programme and open it to such promising areas of research.

Reaching out to a Broader Scientific Community

Despite the numerous challenges posed by space experimentation the programme has managed to set up and maintain a coherent user community. However, this community has had a tendency to involve the same individuals and teams, and therefore the scientific scope of experiments does not appear to evolve at the same pace as it does in the mainstream scientific disciplines.

PROGRAMMATIC RECOMMENDATION 2:
To ensure quality and relevance of science performed under the ELIPS programme, ESA should investigate and implement approaches suited to widen and diversify the basis of the community of users, attracting new scientists and broadening the spectrum of experiments performed in the programme. This could be achieved, for example, through better communication to a wider community of announcement of opportunities and the facilities available through the programme.

Cross-fertilisation

Cross-fertilisation among scientific topics and between teams can identify new interdisciplinary topics that should be investigated; an example relevant to life and physical sciences is the study of dynamics and rheology of blood from the scale of a single cell in the flow to hydrodynamic interactions between cells, and between cells and vessel walls.

PROGRAMMATIC RECOMMENDATION 3:
It is recommended that ESA organises regular networking events and/or user workshops involving representatives from ELIPS investigator teams from the whole spectrum of the programme. Such initiatives would provide a platform for scientists to network and discover cross-disciplinary aspects of their work, and potentially collaborate. Systematic diffusion of information about scientific publications made possible through ELIPS to the whole user community could also catalyse cross-fertilisation.

Infrastructure and Facilities

The programme offers a well-balanced and coherent set of research platforms and facilities, and ground based facilities (GBFs) are perceived to represent a valuable asset. With ISS (International Space Station) operations secured only until 2020, ambitions to perform new investigations in the medium- to long-term can be hampered.

PROGRAMMATIC RECOMMENDATION 4:
Support of GBFs should be continued and even increased, and new mechanisms such as the development of small-scale multi-user instruments to be used in the various GBFs should be implemented.

PROGRAMMATIC RECOMMENDATION 5:
Continuous availability of long-term man-tended in-orbit research facilities is crucial; it is therefore of utmost importance to start preparing for the post-2020 period as soon as possible.

6.1.2 ELIPS programme implementation

Coordination with National Organisations

ELIPS provides a focal point for research at the European level (and beyond) and an anchor for international cooperation. While the programme provides infrastructure, all other means to conduct investigations (including sample/data exploitation) have to be provided by national research organisations. Considering the number of nationalities represented in project teams, this can be a major challenge.

PROGRAMMATIC RECOMMENDATION 6:
Coordination between ESA and national organisations has to be significantly improved, in particular for coordinated and complementary funding of preparatory work on the ground and post-flight analyses of samples and data. It is also crucial that research grants are secured as soon as possible in the process. Reaching a stronger integration of all the experimentations' components and setting up (virtual) common pots of funds dedicated to specific announcements of opportunity could offer a way to streamline programme management while limiting the overall administrative load for the research teams (i.e. applications and paperwork).

Topical Teams

ESA Topical Teams (TT) are very valuable tools that represent the main bottom-up vector between the ELIPS programme and the scientific community. This flexible scheme allows for the coordination of experts pertaining to specific scientific issues relevant to the programme. However, TTs appear often to involve representatives from the historic ELIPS community.

PROGRAMMATIC RECOMMENDATION 7:
Because of its strategic importance and the improved quality it has brought to the programme, the TT scheme should be continued. However, the rather loose selection and implementation procedures do not seem to reflect the importance the TT concept has for the programme. Therefore, the whole TT scheme should be reviewed in detail and restructured. Specifically, issues such as the following should be considered:

- Advertisement of TT opportunities
- Selection process
- Team composition and how to involve newcomers and early career scientists
- Rotation of the coordinator
- Regular review and rotation of TT membership

Mixing Directed Research with Curiosity-driven Activities

ELIPS encourages scientific curiosity and blue sky research. It is also important that the research performed in ELIPS contributes to addressing major scientific challenges. While the current open-ended research solicitation process does not prevent such activities from being proposed and performed, it is clear that it does not motivate pre-defined key issues to be put forward and/or be investigated within ELIPS.

PROGRAMMATIC RECOMMENDATION 8:
Overall, the programme should be more able to address targeted scientific priority topics. Some degree of targeted research should be introduced to mobilise some of the investigations performed towards topics of strategic relevance. This should be based on the inputs and recommendations originating from various sources (e.g. ESF, Topical Teams or ESA's working groups). ESA should investigate ways to mix targeted activities with curiosity driven research.

Announcement and selection of experiments

The ELIPS programme involves different research solicitation approaches and an independent peer-review process. However, the long time between major announcements of opportunity (AOs) and experiment implementation advocates for i) more interaction with the proposers during the selection process and ii) adjusted systematic re-evaluation of the experiments that have been awaiting implementation for more than three years.

PROGRAMMATIC RECOMMENDATION 9:
There is a need to further ameliorate the review process implemented in ELIPS. Implementing a rebuttal step in dedicated AOs would definitely improve the selection process.

PROGRAMMATIC RECOMMENDATION 10:
Experiments awaiting implementation for more than three years should be systematically re-evaluated before entering phase B. The same standards and process implemented for the original evaluation and selection of experiments should be used for this re-validation step.

Increasing the Scientific Outcome of the Programme

Due to specific constraints, ELIPS only provides the opportunity to experiment on small samples and with a small number of subjects. In addition, experiments often cannot be reproduced. Therefore, even if they are sometimes of the highest value, the data produced can be limited, making it challenging for investigators to publish in high impact peer-reviewed journals.

PROGRAMMATIC RECOMMENDATION 11:
The success of the programme should be quantified by its ability to efficiently answer specific questions in a comprehensive manner. The number of experiments implemented is not considered to be a valuable quality control indicator. Therefore, and when relevant, ESA should consider increasing the level of resources allocated to experiments to strengthen their case and the validity of their results even if this implies implementing fewer experiments.

Turnaround Time

In the past, various unpredictable events have had significant impacts on ELIPS implementation (e.g. Foton M1, STS 107) and it is acknowledged that implementing space experiments involves very complex processes. However, in most cases, the time from the AO to actual implementation of an experiment on the ISS exceeds three to five years and can even exceed ten years.

PROGRAMMATIC RECOMMENDATION 12:
ESA should consider implementing fast-track AOs, e.g. dedicated to existing hardware (Kubik, for example) and allowing rapid implementation. Such AOs could be issued every two years.

PROGRAMMATIC RECOMMENDATION 13:
ESA should find a way to identify and list the most efficient practices in terms of programme management (e.g. national Soyuz taxi flights) and development (e.g. involving the scientific team as a subcontractor). This could be made possible via an external audit performed by a contractor.

Reporting and Data Archiving

ELIPS provides support to research projects through use of facilities, equipment and logistical support. However, ground-based preparatory activities, exploitation of data and workforce are funded through other means. This in turn causes issues with implementing compulsory and systematic feedback from the outcomes of performed experiments.

PROGRAMMATIC RECOMMENDATION 14:
ESA should investigate and implement new strategies to improve the flow of information going back to ESA after the experiment has been implemented. This includes acknowledgement of the ELIPS programme, results from experiments, and publications and could involve specific agreements with national research organisations.

PROGRAMMATIC RECOMMENDATION 15:
ESA needs to investigate ways to make the Erasmus Experiment Archive a more reliable, updated and user-friendly database of research findings made possible by the ELIPS programme, for the proper exploitation of such knowledge by the scientific community at large.

6.2 Life Sciences

6.2.1 Overarching life sciences issues

A detailed review of life science research under the ELIPS programme was performed, and specific evaluations were performed (with detailed recommendations) for each sub-discipline. From these analyses, two sets of overarching recommendations emerged, focused on i) the promotion of cutting edge science and cross-disciplinary interactions, and ii) the promotion of an integrated physiology approach.

Promoting cutting edge science and cross-disciplinary interactions in life sciences

OVERARCHING LIFE SCIENCES RECOMMENDATION 1:
Identify and implement mechanisms to ensure faster deployment and use of new investigation techniques and technologies in the programme.

OVERARCHING LIFE SCIENCES RECOMMENDATION 2:
Implement mechanisms to promote interdisciplinary interactions within the life science programme to I) learn from common experiences, II) enhance the use of existing facilities and III) develop more shared instrumentation.

OVERARCHING LIFE SCIENCES RECOMMENDATION 3:
Promote interaction between sub-disciplines such as immunology, radiation biology, microbiology, cell and molecular biology and nutrition, and encourage trans-disciplinary projects, such as integrative physiology, that couple quantitative modelling with experimental work.

OVERARCHING LIFE SCIENCES RECOMMENDATION 4:
Encourage projects that examine the interactions between the living organisms' genome and environmental factors including microgravity, radiation, desiccation, etc.

OVERARCHING LIFE SCIENCES RECOMMENDATION 5:
Refine AOs so that in addition to the provision of projects to test a hypothesis by collecting specific data (hypothesis-driven research), it is possible to propose projects where the emphasis is on collecting large datasets for subsequent analysis and data mining (data-driven research).

OVERARCHING LIFE SCIENCES RECOMMENDATION 6:
Implement a strategy for data sharing, so that communities beyond the current reach of the ELIPS programme can benefit from experiments that have already been carried out.

Integrated physiology

OVERARCHING LIFE SCIENCES RECOMMENDATION 7:
Promote and facilitate the integration of (human) physiology sub-disciplines.

OVERARCHING LIFE SCIENCES RECOMMENDATION 8:
Further address the links between physiology, psychological performance, and human–computer interactions, which have been overlooked up to now.

OVERARCHING LIFE SCIENCES RECOMMENDATION 9:
Increase the capacity to perform research on animals (rodents).

OVERARCHING LIFE SCIENCES RECOMMENDATION 10:
Design and refine cell and animal models specifically suited to address mechanistic issues related to environmental stressors typical of space-flown missions.

6.2.2 Life Sciences Sub-disciplines

Space relevance and achievements of the ELIPS sub-disciplines have been reviewed and specific future priorities and recommendations have been defined for each.

Behaviour and Performance

BEHAVIOUR AND PERFORMANCE RECOMMENDATION 1:
A marked shift of focus should be implemented, particularly where access to the ISS platform is envisaged as a realistic goal for projects in behaviour and performance. In particular, some top-down

guidance is required, promoting the need to address important topics that have been neglected: skill and performance maintenance; monitoring and support for crew members under stress; problems of interaction of crew with complex equipment and automation.

BEHAVIOUR AND PERFORMANCE RECOMMENDATION 2:
There is a need to study crews as teams of operators who carry out mission-related tasks, including a concern with the dynamics of crew cognition and skill flexibility, rather than only in terms of group interaction processes. An important core requirement is the need to develop and implement an integrated monitoring capability for individual crew members, including not only behavioural and interpersonal measures, but also the person's on-going physiological state. In this context it is important to create a strong link between psychological questions and those addressed by neuroscience and cardiovascular and exercise physiology, in the search for underlying compensatory mechanisms and common patterns of adaptation to microgravity.

BEHAVIOUR AND PERFORMANCE RECOMMENDATION 3:
As to methodology, the suggested new directions depend on being able to study effects of the space environment on 'steady state' behaviour in the ISS or ground simulation conditions (i.e. well-learned tasks, with no further improvement occurring during the testing phase, making changes impossible to interpret). This has been a major problem in most previous research on performance, and undermines even the best research plans. It can only be overcome by ensuring that adequate provision of time and opportunity for training, prior to starting testing, is formally built into the human testing schedules.

Exercise, Muscle/Bone

EXERCISE, MUSCLE AND BONE RECOMMENDATION 1:
The mechanisms of adaptation to microgravity and response to exercise in a specific subject are not well characterised. Future studies should be directed towards dissecting the components of structural adaptation related to muscle-derived and gravity-derived loading. Exercise programmes should also be designed to avoid post-loading bone desensitising processes, and be modelled following a more mechanistic and hypothesis-driven approach, based upon recent knowledge on related domains.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 2:
The design and consideration of ground-based analogues are mainly restricted to two models, i.e. HDBR and tail suspension, but other experimental and clinical models such as Ko mice with targeted modification of the bone and muscle adaptive responses and spinal cord injury should be considered.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 3:
Whereas the variability in spaceflight and space-analogue-related bone loss and muscle atrophy have been consistently acknowledged, the factors that influence individual rates of post-flight recovery, and in some individuals the lack of recovery, are still unknown despite more than 20 years of space flights and bed rest studies. These factors should be further investigated.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 4:
Gold standards for human-based exercise experiments should be enforced within the ELIPS programme. As recently outlined for animal-based exercise studies, exercise responses and adaptations should be reported using standardised means to ensure reliable data, appropriate interpretation and comparisons.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 5:
The efficiency of vibration exercise in counteracting bone and muscle wasting during space flight and flight analogue studies is still under experimental scrutiny, in particular because of its potential anabolic effect on bone. Despite its wide use in the ELIPS programme, there are knowledge gaps that should be covered including the mechanism of action and clinical effects, and the heterogeneity of the protocols used. It is also argued that "vibration only" would be of limited value in counteracting muscle atrophy during long duration space flights and HDBR, although a bone effect is feasible.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 6:
The potential dysfunction under microgravity of muscle–bone cross talk by the alterations of its paracrine, autocrine and endocrine constitutive factors, and the modulatory role of its operational state by the neuronal system have not yet been explored under the ELIPS programme. However, the muscle–bone interface is of current interest for the understanding

of bone and muscle metabolism, and a focus on this topic might provide new insights into the functional and developmental interaction between muscle and bone.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 7:
Extending studies to include nutrition–muscle–bone interactions would be challenging in view of the interdisciplinary effort required, but a systematic approach to assess the functional state of the bone–muscle cross-talk system under specific physical exercise and nutrition regimens would enable a wider perspective of the bone and muscle adaptive responses.

EXERCISE, MUSCLE AND BONE RECOMMENDATION 8:
Human primary osteocyte models should be further developed, as they are the master bone cells constituting a matrix-integrated functional syncitium with a plethora of functions involving the control of bone remodelling, contribution to short- and long-term error correction mechanisms in acid–base equilibrium and plasma calcium homeostasis, mechanotransduction processes, microdamage repair, oxygen sensing, vascular control, and production of factors and regulators of mineral and possibly muscle metabolism. Since osteocytes are embedded throughout the mineralised matrix, they present major challenges due to their difficult accessibility and the few models available in vitro displaying all their functions. 3D culture models of bone cells are going to be developed (MEDES–ERISTO programme) on the assumption that primary human osteoblasts can be induced to differentiate into osteocytes in 3D scaffolds. These models should be further implemented since bone remodelling functions require complex 3D arrangement to be fully exploited. Projects in this direction have already been funded by ESA and are essential for adequate investigation of osteocyte metabolism in microgravity.

Cardiovascular and Pulmonary Systems

CARDIOVASCULAR AND PULMONARY SYSTEMS RECOMMENDATION 1:
The two main bottlenecks for experiments involving cardiopulmonary physiology are instrumentation and crew time. Experimental work in prolonged microgravity is constrained because of restrictions on upload that prevent the use of detailed imaging modalities such as MRI. Recent projects have addressed to some extent the problem of developing lightweight instrumentation (e.g. ambulatory blood pressure monitoring), and there is scope for more innovation in this area combined with the instrumentation available on the ISS European Physiology Module. These aspects should be further addressed in the future. The deployment of ambulatory instrumentation also helps to minimise the constraint of available crew time because experimental work can be combined with other crew activities.

CARDIOVASCULAR AND PULMONARY SYSTEMS RECOMMENDATION 2:
There are clear links between the effect of spaceflight on the cardiovascular and pulmonary systems, and the effects on the musculoskeletal system and the response to exercise. Opportunities to bridge these disciplines should be sought.

CARDIOVASCULAR AND PULMONARY SYSTEMS RECOMMENDATION 3:
At present data collected under the ELIPS programme are not always available to the broader scientific community. Research in this area could be stimulated by making these data more widely available, perhaps through a portal similar to the online PhysioBank facility (http://www.physionet.org/physiobank/). Effective data sharing would open up the recordings from previous projects to other communities including physiological modelling. Integrative models of human physiology are becoming widely used research tools because predictive models enable hypotheses to be both tested and generated. This approach can complement microgravity experiments because in a model, gravity is a parameter and can be switched off. Data sharing would enable this type of model to be parameterised and evaluated using recordings from human spaceflight or parabolic flight.

Neuro-vestibular

NEURO-VESTIBULAR RECOMMENDATION 1:
The label “neuro-vestibular” given to this subdiscipline unnecessarily confines the topic of research that should rather represent a small section of the neuroscience discipline. It is recommended to change the label to “neuroscience”, as has already been done in the online Erasmus Experiment Archive, and reflects already on-going investigations in various fields of neuroscience, such as motor control in response to microgravity. This will also emphasise the need to invite the general neuroscience community to perform experiments related to the influence of gravity on neural function in general, including sensorimotor, cognitive, cardiovascular, autonomic, etc. This broadening of the scope, which in part has already become apparent, could also help foster closer cooperation with other sub-disciplines such as rodent research, behaviour and performance, cardiopulmonary, and exercise.

NEURO-VESTIBULAR RECOMMENDATION 2:
Existing facilities to study central-nervous function, such as EEG equipment, should be better promoted (and their use be simplified) to ensure their adequate utilisation.

NEURO-VESTIBULAR RECOMMENDATION 3:
Equipment to generate various levels of artificial gravity between 0 and 1*g*, e.g. a small centrifuge-like off-axis rotator, would generate new experimental possibilities.

NEURO-VESTIBULAR RECOMMENDATION 4:
Since the present neuro-vestibular sub-discipline requires human subjects, crew time is a major bottleneck. There are two possible solutions and both should be pursued. 1) Animal research should be done whenever possible; many questions in neuroscience can be answered at least in part by appropriate vertebrate animal models. 2) Better allocate sufficient crew time to a few excellent projects rather than dividing it up over too many projects, causing experiments to lose quality.

Immunology

IMMUNOLOGY RECOMMENDATION 1:
Encourage a paradigm shift from hypothesis-driven to data-driven experimental approaches in immunological research.

IMMUNOLOGY RECOMMENDATION 2:
Encourage device miniaturisation and automation.

IMMUNOLOGY RECOMMENDATION 3:
Encourage recording detailed knowledge of the genetic makeup (hap-maps) of individuals undergoing space missions.

IMMUNOLOGY RECOMMENDATION 4:
Encourage accurate definition of environmental factors affecting immune responses in space.

IMMUNOLOGY RECOMMENDATION 5:
Encourage increased use of mouse models in space-driven immunological research.

Nutrition and Metabolism

NUTRITION AND METABOLISM RECOMMENDATION 1:
Maintain European leadership in bed rest studies, in particular in relation to countermeasure developments relevant for ground medicine and space flights.

NUTRITION AND METABOLISM RECOMMENDATION 2:
Test a new generation of countermeasures focused on cell alterations (e.g. DNA damage, lipid peroxidation) and tissue atrophy (e.g. sarcopenia, osteoporosis).

NUTRITION AND METABOLISM RECOMMENDATION 3:
Test the interactions between the exposure to ionising radiation, modification of food profiles (e.g. fatty acids, phenolic compounds) and changes in the gut microbiota.

Cell and Molecular Biology

CELL AND MOLECULAR BIOLOGY RECOMMENDATION 1:
Topical team(s) to study systems biology, processes in cell biology and related endeavours should be set-up. Topics for investigation could include: studies of single cells and single molecules; signalling cascades; mechanosensing and mechanotransduction in cells and organs; gene regulation induced by microgravity in animals at different ages and developmental stages; and development of tools to study/ascertain the threshold for mechanosensing. The systems biology approach would utilise transcriptomics, DNA microarrays, proteomics, and other '-omics'.

CELL AND MOLECULAR BIOLOGY RECOMMENDATION 2:
Scientific pursuit in these areas could be much better articulated and justified by clearly distinguishing: (i) activities and approaches with an absolute need for space-flight research/development; and (ii) those involving ground-based (mainstream science) research/development and that of simulated micro- and hyper-gravity effects. Clear statements and rationale of the need for equipment and facilities should be made a priority.

CELL AND MOLECULAR BIOLOGY RECOMMENDATION 3:
Other areas of high priority that should be further considered include: accessing high-level and broadband platforms (imaging centre, transcriptomics, post-translational protein modification, sequencing, etc.); data bank and data sharing facilities for tissue engineering to develop artificial organs, tissues such as vessels, and cancer research; improving on late access times.

Gravitactic and Phototactic Responses in Microbes

GRAVITACTIC AND PHOTOTACTIC RESPONSES IN MICROBES RECOMMENDATION 1:
The genetic manipulations performed in *E. gracilis* are essential for proving the functional importance of specific genes. This is currently performed by a transient gene knock-down technology (RNAi). It is to be expected that in the near future, proper gene knock-outs could be made in this organism, and this methodology should then rapidly be embedded in the investigations performed.

GRAVITACTIC AND PHOTOTACTIC RESPONSES IN MICROBES RECOMMENDATION 2:
The gravitaxis studies in *Euglena* should be extended to involve one or two other relevant and evolutionary distant organisms. A suggestion would be filamentous fungi, where several species can detect and respond to both gravity and light. In addition, these fungal systems are amenable to genetic manipulation and would potentially bring new functional information to the current working model on gravitaxis.

GRAVITACTIC AND PHOTOTACTIC RESPONSES IN MICROBES RECOMMENDATION 3:
Bringing modellers/theoreticians into the project would provide a systems biology approach to gravitaxis. In particular, this would allow for interesting modelling of the working hypothesis and bring a broader interdisciplinary community into the group. In addition, the model should try to encompass signalling interactions – in this case between the gravitactical and light responses. The only way these questions can be experimentally proven is to go to space and investigate the phototaxis response in wild-type and specific signalling/sensing mutants.

GRAVITACTIC AND PHOTOTACTIC RESPONSES IN MICROBES RECOMMENDATION 4:
The microscopy system for studies on gravitactic responses should become an open facility for ground-based research in general (at least for space relevant projects) and should be open for other researchers to utilise. It should also be adopted and used for space flights. Having this microscopy system in space would allow for similar kinds of gravitational studies on other unicellular algal systems and be a good avenue for fast-track AO calls in the future for space research.

Microbiology

MICROBIOLOGY RECOMMENDATION 1:
A much stronger systems biology aspect should be incorporated into the investigations. This is particularly valid for the vast genome-wide data that is being generated in space. Setting the recorded regulator changes in perspective will be a major challenge in the future and will require close links to theoreticians/modellers.

MICROBIOLOGY RECOMMENDATION 2:
Investigations should be linked to further laboratory automation, which is a challenge in particular for -omics related data. The lab-on-a-chip approach is well suited for yeast studies, and yeast would in this context provide a good raw model for these types of developments, based on the great amount of background information available. Automation of -omics data is an important development that could be implemented not only for microorganisms but also for higher, more complex systems.

MICROBIOLOGY RECOMMENDATION 3:
Another important future development includes tools for following dynamic processes in cells in real time under microgravity conditions. An important resource in yeast is a complete collection of GFP-tagged proteins, enabling production, localisation and degradation studies in real time. The development of this kind of high-resolution microscopy and online imaging system would certainly open up many new avenues for interesting high-resolution studies in cell biology in space.

MICROBIOLOGY RECOMMENDATION 4:
The completely sequenced clean lineages of yeast in functional studies should be utilised, which will highlight and give important information on the impact from the genetic background to various responses to microgravity.

Astrobiology

ASTROBIOLOGY RECOMMENDATION 1:
Based on past and current experience, continue to develop new orbital exposure facilities both inside and outside spacecraft. Develop systems capable of *in situ* monitoring of microbial growth in Earth orbit (e.g. Cubesats).

ASTROBIOLOGY RECOMMENDATION 2:
Develop access to space beyond low Earth orbit to allow for experiments in more realistic interplanetary radiation environments.

ASTROBIOLOGY RECOMMENDATION 3:
Develop facilities that mimic temperatures found in the interplanetary environment and on other planetary bodies for ground- and space-based research.

ASTROBIOLOGY RECOMMENDATION 4:
Accelerate the development and access of new astrobiology research facilities from the time of proposal acceptance to the time of implementation.

ASTROBIOLOGY RECOMMENDATION 5:
Improve access to ground-based facilities as well as the support to use them.

ASTROBIOLOGY RECOMMENDATION 6:
Implement mechanisms to allow interaction with other ELIPS domains such as physiology/microbiology, to learn from common experiences, develop common instrumentation, and prevent duplication of experiments.

Plant Biology

PLANT BIOLOGY RECOMMENDATION 1:
New blood must be brought into the field, either via TTs and/or by engaging more broadly the scientists in plant biology who are not regularly involved in space experimentation. A young investigator programme could also help.

PLANT BIOLOGY RECOMMENDATION 2:
Facilities need to be brought up to the standards and expectations of the 21st century. There is a need to have RT-PCRs; use of GFPs in flight; confocal and other microscopies and imaging capabilities; sensors and analytical equipment (nutrient, water, oxygen and carbon dioxide) for real time monitoring of aerial and root zones; systems to detect/manage contamination in flight; better controlled environments for various aspects of plant growth/development (T, radiation, airflow; ventilation, gas composition).

PLANT BIOLOGY RECOMMENDATION 3:
Research programmes should be extended to all aspects of gravitropic responses, including how different cell types respond. Other emphases are needed on hypergravity. There is also a need to study broader aspects of gravitropic effects in woody plant forms (stem realignment and branching, for example); these seem to be missing at present. More hypothesis-driven approaches are also needed.

Developmental Biology

DEVELOPMENTAL BIOLOGY RECOMMENDATION 1:
Overall, an urgent priority for this sub-discipline should be to encourage a clear review and prioritisation of research objectives for understanding how gravity influences developmental biology of animals and plants. It is important to establish how experiments in microgravity will offer a detailed mechanistic insight into the process of development, and to carefully consider how information at the molecular level will be linked to larger-scale effects such as morphogenesis. Additionally, there should be a widening of the participation to relevant and productive groups at the forefront of science who have not been involved in microgravity research up until now. This could be implemented through the formation of a TT focused specifically on developmental biology. There should also be a coordinated consideration of what are the best technologies that can be brought to bear.

DEVELOPMENTAL BIOLOGY RECOMMENDATION 2:
It is crucial to initiate a discussion about the question of whether studies in animal developmental biology should be restricted to the cellular level (fertilised eggs, myocytes, stem cells, etc.) or whether also embryos, larvae and juveniles could be included in the search for general principles of development such as critical periods or age-related sensitivities. A clear decision about the use of animals from the embryonic up to the juvenile stages should be implemented in each coming announcement of flight opportunity.

DEVELOPMENTAL BIOLOGY RECOMMENDATION 3:
Once the important research questions have been identified and prioritised, areas having synergy with other programmes (e.g. plant biology, neuroscience) should be identified so that coherent strands of research can be specified within an AO.

Biological Effects of Radiation

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 1:
Efforts should be made to enlarge the expertise of the existing TTs by welcoming new experts in from the broad, interdisciplinary field of radiation biology (it currently appears to be restricted to a few groups/disciplines). This should attract active research groups involved in radiation biology investigations that are still missing in the present ELIPS programme and build broader research proposals for future flight opportunities. Future proposals should also include interdisciplinary aspects with the immune, cardiovascular and central nervous system communities, particularly when space experiments are concerned.

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 2:
NASA has developed a dedicated space radiation biology research laboratory at Brookhaven National Laboratory and efforts should be made to participate in joint projects by combining complementary expertise for assessing the damaging effects of radiation on the genome. One may also recommend continuing to organise joint international workshops with scientists involved in space radiation biology such as the annual Workshop on Radiation Monitoring for the International Space Station (WRMISS) series.

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 3:
There is also a need to further develop computational modelling and simulations to enable a better understanding of molecular effects of CGR on key cellular molecules and the biological consequences, particularly in terms of late effects (cancer).

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 4:
Access to ground-based research facilities with emphasis on ion accelerators should be facilitated at GSI with a possible extension to GANIL at Caen (France) where a biology laboratory has been created.

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 5:
There is a need to implement equipment on the ISS for performing experiments on animals to further investigate the effect of microgravity on the biochemical processing of radiation-induced cellular damage. For this purpose, animal facilities and radiation sources are required on board.

BIOLOGICAL EFFECTS OF RADIATION RECOMMENDATION 6:
Participation in major scientific events such as the annual or international radiation research meetings by having, for example, a symposium dedicated to space radiation biology should be encouraged. This also concerns the already successful policy of publication of research findings and review articles in journals with a high impact factor.

Radiation Dosimetry

RADIATION DOSIMETRY RECOMMENDATION 1:
Research activities in the domain of space radiation dosimetry have matured gradually and have had major achievements involving a broad international scientific community, with Europe as a major leader. Future efforts should focus on the development of passive and active shielding materials together for temporary shelters necessary for lowering radiation risk to humans, particularly for long-duration exploration missions and extravehicular activities. This also concerns the development of individual detectors and real-time detection of radiation components that should involve real-time calibration for a better assessment of dose exposure. This would require implementation of additional instruments on board the ISS and access to ground-based ion accelerator facilities provided by ESA at GSI. Also, additional efforts have to be made for better forecasting of solar events and the development of improved transport codes and radiation modelling.

RADIATION DOSIMETRY RECOMMENDATION 2:
A more integrated approach should be taken that includes and strengthens cooperation with the radiation biology community, allowing a better delineation of the biological effectiveness of radiation and individual dose in inner organs.

6.3 Physical Sciences

6.3.1 Overarching physical sciences issues

Overall, it should be emphasised that there are some truly outstanding experiments found in the physical sciences portfolio of ELIPS, and therefore continuation of the ELIPS programme should be given the highest priority. Through the evaluation of specific sub-disciplines, several overarching recommendations for the physical sciences emerge.

OVERARCHING PHYSICAL SCIENCES RECOMMENDATION 1:
In many projects, the justification of microgravity was not entirely convincing, or was even poor. In particular, before experiments involving 'model systems' are funded, possible alternative routes to answering the scientific questions posed, such as computer simulation or ground-based model systems, should be examined with scrutiny.

OVERARCHING PHYSICAL SCIENCES RECOMMENDATION 2:
In several projects, it was not entirely clear how space-borne research related to ground-based research, and why the former would be so indispensable to the latter. The need for (many) preparatory ground experiments must be justified in future proposals and activities. In particular, wherever the term 'model system' is being used, we strongly encourage a closer look at what is being proposed as a model for what, and to consider the well-developed possibilities of doing numerical simulations instead.

OVERARCHING PHYSICAL SCIENCES RECOMMENDATION 3:
Wherever industrial applications are put forward as a justification for microgravity research projects, it should be made very clear and explicit exactly what application is expected to benefit from the results, in what respect, and in what time frame. There should be a proven industrial interest of the very experiment under consideration in order to underpin the application relevance. The best and most obvious way for industry to prove such interest is by providing a substantial financial contribution to project funding.

OVERARCHING PHYSICAL SCIENCES RECOMMENDATION 4:
The varying degree of scientific quality of the projects reflects some room for improvement in the review process. In general, it appears that fewer projects should be funded, and given more funds individually.

6.3.2 Physical sciences sub-disciplines

Space relevance and achievements of the ELIPS sub-disciplines have been reviewed and specific future priorities and recommendations have been defined for each.

Cold Atom Sensors and Related Fundamental Physics Missions

COLD ATOM SENSORS AND RELATED FUNDAMENTAL PHYSICS MISSIONS RECOMMENDATION 1:
To best meet the mission goals of ACES, ESA should engage the participation of as many precision time-keeping laboratories world-wide as possible. This in turn will create a unique global time-keeping network with capabilities beyond anything possible without ACES that will have significant terrestrial impact beyond the fundamental science motivation of the project.

COLD ATOM SENSORS AND RELATED FUNDAMENTAL PHYSICS MISSIONS RECOMMENDATION 2:
A long-term strategy for use of atom interferometery and space-clock technology should be developed within ESA, starting with a strategy that reaches across ESA directorates. The planning should also be done in cooperation with other agencies both inside and outside the EU.

COLD ATOM SENSORS AND RELATED FUNDAMENTAL PHYSICS MISSIONS RECOMMENDATION 3:
Fundamental physics of particles at the highest possible energies demands access to space using large observatories. The JEM–EUSO experiment is an excellent example of important progress in this field. ESA should plan projects and collaborations to retain leadership at this frontier. It should continue to support this project for possible deployment by the second half of this decade.

COLD ATOM SENSORS AND RELATED FUNDAMENTAL PHYSICS MISSIONS RECOMMENDATION 4:
Fundamental physics experiments in general are very technologically demanding and require significant R&D investment. The SOC project is an excellent example. It is imperative that R&D investment be coordinated between ESA fundamental physics projects, between various funding sources outside of ESA, and in cooperation with industry. This will not only increase efficiency and flight readiness, but it will foster technological spin-offs and increase the potential economic impact of space flight.

Atmosphere Observations

ATMOSPHERE OBSERVATIONS RECOMMENDATION 1:
The planned programmes should be completed. Further delays in experimental development severely hamper the advancement of scientific research objectives and should be avoided. Given the development time that has elapsed, the programmes could potentially benefit from a review of specific scientific objectives to evaluate which of the experiments need to be fine-tuned or updated, while not altering the installation development.

ATMOSPHERE OBSERVATIONS RECOMMENDATION 2:
While there is broad relevance to Earth-based research in the ICAPS programme, the direct link, particularly in terms of practical translation of the space-borne research, needs to be better elaborated and justified.

ATMOSPHERE OBSERVATIONS RECOMMENDATION 3:
Dissemination of results needs to be improved. ESA and/or ELIPS should be clearly acknowledged wherever involved.

Soft Matter: Dust Particles, Colloid Physics and Complex Plasmas

SOFT MATTER RECOMMENDATION 1:
Studies of systems containing particles of micrometre size and larger should be continued under microgravity conditions. The results are of potential importance for the broader physics community.

SOFT MATTER RECOMMENDATION 2:
In the experiments devoted to electro-rheological plasmas, more complex spatial structures should be looked for, and the possibility of inducing shear flow should be examined.

SOFT MATTER RECOMMENDATION 3:
Great care should be taken that only those scientific questions are posed (and corresponding experiments flown) which cannot be answered by means of ground-based experiments or computer simulation. The latter applies specifically if so-called model systems are being investigated.

Fluid Dynamics

FLUID DYNAMICS RECOMMENDATION 1:
Experiments would greatly benefit from improved downloading and zipping capabilities on the ISS. As a general remark, there should be better synchronisation and a shorter time lapse between the timing of AOs and missions.

FLUID DYNAMICS RECOMMENDATION 2:
From the technical point of view, vibration devices for fluids with a large range of amplitude and frequencies and good temperature control are required.

FLUID DYNAMICS RECOMMENDATION 3:
Whenever relevant to the problem at hand, theoreticians should consider extending their techniques, which are so far essentially based on partial differential equations such as Navier– Stokes, diffusion equations etc., to other methods where one can model several processes at a more fundamental level. These methods include lattice Boltzmann simulations, dissipative particle dynamics, and stochastic rotation dynamics. The advantage of these models over macroscopic models is the representation of the interfaces which are not sharp but diffuse.

Phase Change and Heat Transfer

PHASE CHANGE AND HEAT TRANSFER RECOMMENDATION 1:
Results and data obtained in the context of ELIPS should be better disseminated and made available to the scientific community, acknowledging ESA and ELIPS wherever appropriate and by publishing in journals with high impact factor.

PHASE CHANGE AND HEAT TRANSFER RECOMMENDATION 2:
The research effort should focus on specific phenomena where the elimination of buoyancy and convection is really crucial.

PHASE CHANGE AND HEAT TRANSFER RECOMMENDATION 3:
Access to microgravity and ISS experiment facilities should be maintained, as far as it is scientifically well justified.

Complex Fluids: Foams, Emulsions, Granular Materials

COMPLEX FLUIDS RECOMMENDATION 1:
It is recommended that within the complex fluids projects, priority is given to fundamental research on foam systems, in particular on dynamics of purely aqueous foams and on the physics of metal foams and the role of additives therein. These projects are furthermore expected to fertilise each other. Since metal foams are among the super-materials of the future and still bear an enormous potential for process innovations, this research should be given high priority in the complex matter space research community.

COMPLEX FLUIDS RECOMMENDATION 2:
It is recommended that only the high scientific quality projects be considered for funding, in order to promote high level publication. In this context, a critical eye on the necessity of microgravity will be important.

Material Science: Metallurgy and Crystallisation

METALLURGY AND CRYSTALLISATION RECOMMENDATION 1:

Experiments aimed at obtaining novel materials should have priority over those aimed at improving well-established materials. Alternatively, the companies or entities which can benefit from those advances should bear a significant part of the costs.

METALLURGY AND CRYSTALLISATION RECOMMENDATION 2:

In the case of purely fundamental research, each project should contain a clear statement about the breakthrough in knowledge expected from experiments carried out in microgravity with respect to ground experiments. The high costs of space research are justified only if the expected results considerably add to the body of knowledge in a given field and/or pave the way to a conceptually new field.

METALLURGY AND CRYSTALLISATION RECOMMENDATION 3:

The planned use of already existing facilities (furnaces, microscopes, spectrometers, etc.), established over decades with substantial investment, cannot be considered to be a sufficient motivation for new projects. The expected scientific output (fundamental knowledge or novel materials) is the only parameter to be considered when judging future projects.

METALLURGY AND CRYSTALLISATION RECOMMENDATION 4:

The number of the expected preparatory ground experiments has to be clearly stated. Normally, the time investment for terrestrial work should be comparable with that required to plan and execute space experiments. Strong deviations from a correct ratio should be foreseen and justified in the proposals. This is in order to avoid the word "microgravity" to be taken as alibi for long-lasting ground research.

Annexes

Professor Roberto Battiston

Professor Battiston was born in Trento in 1956, obtained his Laurea degree at Scuola Normale di Pisa (1979), and is currently the Chair of General Physics at the Engineering Faculty of the Perugia University, Faculty of Engineering (since 1992). Laurea honoris causa University of Bucharest (2000). He has worked for over 20 years in international collaborations in the field of experimental physics and fundamental interactions, including: strong interactions, electroweak interaction physics, and search for antimatter and dark matter in cosmic rays. He is the founder of a research group in Perugia, active since the beginning of the 1990s, in the field of frontier detectors and technologies to be used in ground- and space-based fundamental physics research. In 1994, he founded SERMS (Laboratory for the Study of the Effects of Radiation on Spacial Materials), devoted to the characterisation of materials and devices to be used in space conditions. Additionally, he is deputy spokesperson for the AMS experiment, a large particle physics experiment approved on the International Space Station, successfully flown during the STS-91 Shuttle flight in June 1998 and deployed on the ISS in May 2011. He is author of more than 420 papers published in international scientific journals, and organiser of several workshops devoted to space science and to advanced technologies (Trento 1999, Elba 2002, Washington 2003, Beijing 2006). Committee memberships include: Scientific Coordinator in the First Scientific Committee of INFN for six years; Member of the Scientific Council of IRST (Trento) (1995); Member of the ASI Scientific Committee (1997–1999); Member of the Scientific Council of IFC Milano (1998–2002); Member of the ESA Fundamental Physics Advisory Group (1999–2001); Member of the Joint Space Science Advisory Group (JSSAG; 2001); Director of the Perugia INFN Section and member of the National INFN Directorate (2001– 2007); Member of the INAF Board of Directors (2004–2007); President of the INFN National Committee on Astroparticle Physics (since 2009); Member of the National Committee for the Evaluation of Research (since 2012).

Dr Salim Belouettar

Dr Belouettar is a Senior Scientist and Head of the Modelling and Simulation research team at the Centre de Recherche Public, Luxembourg. He studied civil engineering and mechanics of materials, receiving his Engineering Diploma in 1992. Dr Belouettar joined the University of Lorraine, France in 1993 where he conducted scientific research in the field of computational mechanics. He obtained his PhD diploma from the same university in 1997. In 2001, Dr Belouettar joined the Modelling and Simulation group of the Centre de Recherche Public Henri Tudor as a senior R&D engineer. His research work includes the development and validation of reliable models and efficient simulation tools to describe and understand complex non-linear systems, both natural and engineered, on a wide range of spatial and temporal scales, with an emphasis on advanced materials and structures. During his career, Dr Belouettar has collaborated with world leading industries such us EADS, and Arcelor Mittal and successfully headed many national and European projects on these topics. In 2010 he obtained his habilitation (highest academic degree in France) in Engineering Science from the University of Strasbourg. He has published about 70 papers in international journals.

Professor Nicholas Bigelow

Professor Bigelow received his MS and PhD (1989) in physics from Cornell University. He then joined the Technical staff of AT&T Bell Laboratories, where he remained until 1991. Early in 1991, he moved to the Ecole Normale Superieure in Paris, France where he worked in the Laboratoire Kastler-Brossel. Professor Bigelow joined Rochester University in 1992, where he presently holds the position of Professor of Physics and of Optics and chair of the department physics and astronomy (since July 2007). Professor Bigelow is the Chair of the Fundamental Physics Discipline Working Group in the NASA Microgravity Physics Programme, he has served as an invited researcher in the laser cooling groups at the Laboratoire Kastler-Brossel in Paris, France, the Institude d'Optique in Orsay, France and at the University of Sao Paulo in Brazil. Professor Bigelow was elected Fellow of the American Physical Society in 2004, and Fellow of the Optical Society of America in 2007. In 2004 he was selected as a Topical Editor for *Optics Letters* which is published by the Optical Society of America.

Professor Anders Blomberg
Professor Blomberg completed his PhD in microbiology in 1988 at the University of Gothenburg with the thesis *"Osmoregulation and Osmotolerance in Yeast"*. During his PhD he spent a year in the laboratory of Professor Duncan Brown, University of Wollongong, Australia. He now holds a position as Professor in Functional Genomics. Between 2001 and 2008 Professor Blomberg was director of the National Research School in Genomics and Bioinformatics. He has currently 65 primary publications in international journals and runs a research group of around ten members composed of a mix of PhD students and post-docs. Current research interests of Professor Blomberg include: i) study of the mechanisms involved in the yeast stress response, ii) phenomics – developing methodologies for large-scale phenotypic profiling of yeasts, and iii) functional genomics of the barnacle Balanus improvises.

Professor Jean Cadet,
Chair: Life Sciences
Professor Cadet is Scientific Adviser at the French Atomic Energy Commission, CEA/Grenoble and Adjunct Professor, University of Sherbrooke, Sherbrooke, Canada after being the head of the Laboratory of "*Lésions des Acides Nucléiques*" and Research Director at CEA. He is involved in research activities that deal with various aspects of the chemistry and biochemistry of oxidatively generated and photo-induced damage to DNA. He is author or co-author of 550 publications consisting of more than 480 original contributions to peer-reviewed journals and about 70 book chapters. His "h" factor is 61. He has been and is a member of the editorial board of several journals: *Chemical Research in Toxicology* (until 2009), *Free Radical Research* (until 2009), *Free Radical Biology and Medicine*, *Mutation Research*, *Indian Journal of Radiation Research, International Journal of Radiation Biology, International of Low-Dose Radiation Biology*. He has recently been appointed Associate Editor of *Radiation Research* and *Journal of Biochemical Technology*, and since 2009 he has been the Editor-in-Chief of *Photochemistry and Photobiology*. He has received several awards including "*Armes Lecturer*" from the University of Manitoba at Winnipeg, "*Weiss Medal*" from the Association for Radiation Research, UK, "*Grand Prix Scientifique*" from CEA, "*Research Award*" from the American Society for Photobiology and the "*Medal for Excellence*" from the European Society for Photobiology. He has also received the "*Prix Charles Dhéré*" in chemical biology and the "*Médaille Berthelot*" in chemistry from the French Academy of Sciences. He has been promoted to "Chevalier de l'Ordre National du Mérite" by the French Minister of Universities and Research.

Dr Richard Clayton,
Rapporteur: Life Sciences
Dr Clayton is Reader in Computer Science at the University of Sheffield in the UK. Following a BSc in applied physics, and PhD in medical physics, he worked from 1990 to 1998 at the Freeman Hospital in Newcastle upon Tyne. The main focus of his work was a detailed study of signals recorded from patients at risk of an electrical disorder called ventricular fibrillation (VF). VF is responsible for many cases of sudden cardiac death, and is characterised by electrical anarchy rather than control of normal heart rhythm by the heart's natural pacemaker. This work was funded by Fellowships from the British Heart Foundation, and in 1998 a further British Heart Foundation Fellowship enabled a move to the University of Leeds to develop computational models of electrical activity during VF. His current interests now range from the clinical applications of computer models and computational imaging, to the use of high performance computing, and through to the insights into human physiology that these tools provide. He has published widely in clinical, physiological, and non-linear physics journals.

Professor Roberto Fornari
Professor Fornari is presently Professor at the Physics Department of the Humboldt University Berlin and director of the Leibniz Institute for Crystal Growth (IKZ) in Berlin (joint employment). He studied physics at the University of Parma, Italy, where he graduated in 1980. Before moving to Berlin he has worked for more than 20 years as a research scientist at the Institute for Electronic and Magnetic Materials (IMEM) of the Italian National Research Council where he led different research projects on growth and characterisation of compound semiconductors. Professor Fornari has authored/co-authored about 190 scientific papers, nine patents and different book chapters. He has edited books and proceedings on crystal growth and materials

science, and is member of the editorial board of *J. Crystal Growth*, *Cryst. Res. Technol.*, *J. Optoelectronics* and *Advanced Materials*. He was elected President of the International Organisation for Crystal Growth (IOCG) for the triennium 2010–13.

Dr Stefan Glasauer
Dr Glasauer is a senior researcher and Head of the Centre for Sensorimotor Research at the Ludwig-Maximilians-Universität München (LMU). He studied electrical engineering at the Technical University Munich and received his Dr-Ing degree in engineering in 1992 as a fellow of the Max-Planck-Institute for Behavioral Physiology. He then joined the Laboratoire de Physiologie de la Perception et de l'Action at the Collège de France in Paris with a postdoctoral fellowship from the CNRS. He participated as co-investigator in the MIR'92 mission and the EUROMIR'94 mission, several parabolic flight campaigns, and the NASA Extended Duration Orbiter Medical Projects DSO 604 and 614. In 2005 he obtained his habilitation (highest academic degree in Germany) in experimental neurology and clinical neurophysiology. His research interests include human spatial orientation and navigation, the vestibular system, motor control of eye and head movements in health and disease, cortical optic flow processing, and human–robot interaction. His methods reach from computational neuroscience and probabilistic modelling over psychophysics to behavioural physiology and functional magnetic resonance imaging. He is founding member and principal investigator at the Bernstein Center for Computational Neuroscience Munich, a member of the Board of Directors of the Integrated Research and Treatment Center for Vertigo, Oculomotor and Balance Disorders, a member of the Extended Board of the cluster of excellence CoTeSys (TU Munich), and a member of the Scientific Board of the Graduate School for Systemic Neurosciences at the LMU. He teaches at the LMU and the Technical University Munich and has published more than 120 papers in international journals.

Professor Daniel Gopher
Professor Gopher is a Professor Emeritus of Cognitive Psychology and Human Factors Engineering and held the Yigal Alon Chair for the Study of Human at Work. He is a fellow of the US Human Factors and Ergonomics Society and the International Ergonomics Association. Since 1980 he has been the director of The Research Center for Work Safety and Human Engineering, an interdisciplinary research centre. In 1996 he established, together with Professor Asher Koriat from Haifa University, the joint Technion-Haifa University Max Wertheimer Minerva Research Center for Cognitive Processes and Human Performance. Professor Gopher joined the Technion Faculty of Industrial Engineering and Management in 1979, after serving 12 years in the Israel Defence Forces, during which time he was a senior scientist and acting head of the Research Unit in the Personnel Division (1966–1970), and Senior Scientist and Head Human Factors of the Air Force (1970–1979). Professor Gopher's research focuses on the study of human attention limitations, measurement of mental workload, training of complex skills, and their applications to the design of aviation systems, medical systems, safety at work, and development cognitive trainers and virtual reality multimodal training platforms for complex skills.

Professor Stephan Herminghaus,
Rapporteur: Physical Sciences
Professor Herminghaus is a German physicist. He received a PhD in physics from the University of Mainz in 1989. His postdoctoral stay was at the IBM Research Center in San Jose, California (USA), in 1990. He completed his habilitation at the University of Konstanz in 1994 and was the head of an independent research group at the MPI for Colloids and Interfaces, Berlin, from 1996 until 1999. He then became a full professor at the University of Ulm from 1999 until 2003. Since 2003, he has been a director at the Max Planck Institute for Dynamics and Self-Organisation, Gottingen. Since 2005, he has had an additional appointment as an Adjunct Professor at the University of Göttingen. Further, he was appointed as Professeur Invité at Université Paris VI for the winter term 2006/7.

Professor Dr Siegfried Hess
Born 1940 in Hof/Saale, Bavaria, Germany, Dr Hess studied mathematics and physics at the University of Erlangen-Nürnberg, Germany, 1964 Diploma (master) in physics, 1967, with a promotion to Dr rer. nat. (PhD) in Erlangen, 1970 habilitation (Privatdozent) in physics. He has been a graduate student, postdoc and visiting professor at the

Universities in Minneapolis, Minnesota, USA; Leiden, Holland; Toronto, Canada, and again in Leiden. From 1978 to 1984 he was a Professor (C3, associate professor with tenure) for theoretical physics in Erlangen, and from 1984 to 2007, a Professor (C4, full professor) at the Institute for Theoretical Physics of the Technical University Berlin (TUB). Guest scientist and visiting professor at the National Bureau of Standards (NBS, now NIST) in Boulder, Colorado US; at the Institute Laue-Langevin (ILL) in Grenoble, France; at the Australian National University in Canberra and at the University of California at Santa Barbara, US. Served as Head of the Institute for Theoretical Physics, as Dean of the Faculty of Physics at the TUB, chairman of the section Dynamics and Statistical Physics of the German Physical Society (DPG), chairman of the collaborative research projects anisotropic fluids and elementary friction processes of the German Science Foundation (DFG), member of committees for the evaluation of national and international research proposals. Collaborations leading to joint publications with more than 100 scientists from 20 countries. Over 250 scientific publications, dealing with the foundations of statistical physics and non-equilibrium molecular dynamics (NEMD) computer simulations, applications to the material properties of molecular gases, plasmas, simple and complex fluids, liquid crystals, polymeric liquids, magneto- and electro-rheological fluids, as well as to solid friction and plastic flow of metals.

Professor Bob Hockey

Professor Hockey is Emeritus Professor of Human Factors and Cognitive Engineering in the Department of Psychology at the University of Sheffield, UK. He has published over 150 research articles and edited or written five books. He is a member of ESA's peer review panel and Coordinator of the ESA Topical Team on assessment of Human Performance in Extended Space Operations. He has worked extensively with ESA over a 25-year period as a member of the LTPO Space Psychology Advisory Group and Human Simulation Studies Planning Group, and has conducted a programme of space-relevant research on skill maintenance and adaptive automation. He coordinated a research network in FP3 as part of a concerted action on effects of stress on human performance, and the FP5 project, IMMORTAL, on driving testing and certification, and is coordinator of the psychology and human machine systems cluster of the THESEUS FP6 project on human space exploration. He has acted as a consultant on human performance and human factors issues to the Institute of Naval Medicine and UK Nuclear Safety Review Committee, and is a member of the council of Rail Research UK (National Centre for Rail Systems Research). He was Director of the NATO ARW on Operator Functional State and Complex Task Performance, and member of NATO (RTO) Human Factors and Medicine Panel task group on operator functional state.

Dr Norman G. Lewis

Dr Lewis currently holds positions of Regents Professor and Director, Institute of Biological Chemistry, at Washington State University. He has received numerous forms of recognition including being elected to Corresponding Fellow of the Royal Society of Edinburgh, Scotland's National Academy of Science and Letters. He has held many leadership positions in various learned societies, such as President of the American Society of Gravitational and Space Biology (ASGSB) and President, Phytochemical Society of North America (PSNA), as well as other responsibilities/offices with the American Chemical Society and other professional organisations. Among editorial board responsibilities, he is Regional Editor of *Phytochemistry*. He also serves on several scientific editorial boards, federal and international grant review panels, and scientific advisory boards worldwide. Dr Lewis' current research interests are largely in discovering/studying/modifying plant biochemical pathways, with an emphasis on lignin/cell wall formation/lignan and allylpropenyl phenol biosynthesis. His laboratory discovered the "dirigent" proteins, the first example of control over radical–radical phenolic coupling *in planta*, and which led to anticancer compounds such as podophyllotoxin and etoposide. He has published in excess of 220 scientific papers and patents, and personnel from his laboratory now hold academic positions in the US, Canada, Brazil, China, France, Japan, Korea, New Zealand, Thailand, and the United Kingdom. Dr Lewis was initially trained in chemistry (natural product/organic chemistry/biochemistry specialisations) receiving BSc and PhD degrees from the University of Strathclyde (Glasgow) and University of British Columbia, where he received ICI and NATO/SRC scholarships to support his studies. He next worked with Professor (Sir) Alan R. Battersby on Vitamin B12 biosynthesis at the University of Cambridge through NRC (Canada) post-doctoral support, prior to taking up a NRC (Canada) Research Associate position. Dr Lewis has also previously held positions as Group Leader at PAPRICAN (Pulp and Paper Research Institute of Canada), and as Associate Professor at Virginia Tech. His research has largely been supported by the US Department of Energy, National Aeronautics and Space Administration, National Institutes of Health, National Science Foundation, US Department of Agriculture, as well as from Thomas G. and Anita Hargrove Foundation, and the Arthur M. and Katie Eisig-Tode Foundation.

Professor Michael H. Loretto,
Chair: Physical Sciences

Professor Loretto is Emeritus Professor in the University of Birmingham. In 1955, he Graduated B Met (Hons) from the University of Sheffield. Between 1955 and 1966, he was Research Officer at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Melbourne, Australia. Between 1966 and 2001, Professor Loretto worked at the university of Birmingham as lecturer, professor, head of department, and director of the Interdisciplinary Research Centre in Materials and of Rolls-Royce University Technology Centre. Professor Loretto has been awarded many medals and scientific distinctions including the David Syme Medal (1961, Australia), doctorate in science (1972, University of Birmingham), the Metal Society Prize for elegant work (1978), the Sydney Gilchrist Medal (1988, Institute of Metals London), Honorary Professorship at IMR (2000, Chinese Academy of Sciences), Order of the British Empire for services to technology transfer and materials science (2000), Hsun Lee award (2001, IMR – Chinese Academy of Sciences). In 2003 he was elected to the Japan Institute of Metals and in 2006 he became Honorary Professor at Huazhong University (China). Professor Loretto is also a member of several international committees: (i) Member of High level DTI Mission to Japan. (ii) European COST technical committee for materials. (iii) Panel to assess CSIRO materials programme. (iv) Research Board for Light Metals research activity in Australia. He has authored over 250 publications; two books on electron microscopy and supervised about 100 PhD students.

Dr Rocco Mancinelli

Dr Mancinelli, microbial ecologist/astrobiologist, is a senior research scientist with the Bay Area Environmental Research Institute at NASA Ames Research Center in Mountain View, CA, US. He has a PhD in microbial ecology from the University of Colorado at Boulder. His research is broad, encompassing ecology, physiology, biogeochemistry, and biodiversity. The common thread that ties his research projects together is the search for the definitive environmental limits in which life can arise and evolve in a planetary context. His research has taken him from the mountaintops of the Andes to the bottoms of the lakes in the Dry Valleys of Antarctica. He has designed and developed bioreactor systems for understanding the relationship between microbes and their environment. Of particular interest is understanding how genetically modified organisms interact with other organisms and their environment using bioreactor systems. Dr Mancinelli has been either a principal investigator or co-investigator on several space flight experiments with microbes both on satellites (e.g. BioPan, GeneSat, and O/OREOS) and ISS (e.g. EXPOSE R and E). Dr Mancinelli is a Fellow of the California Academy of Sciences and the Explorers Club.

Professor Umberto Marini Bettolo Marconi

Professor Marconi is Professor of Condensed Matter Physics in the School of Sciences and Technologies at the University of Camerino, Italy. He graduated in Physics from the University la Sapienza in Rome and obtained a PhD in physics with Summa Cum Laude. He was a postdoc of Professor Norman H. March at the University of Oxford and of Professor Robert Evans at the University of Bristol. He was research associate at Istituto Nazionale di Fisica Nucleare and visiting professor in the Universities of Madrid, Palma de Mallorca. He is author of more than 130 scientific papers in international research in international research journals and has organised more than five international conferences.

Professor Colin O'Dowd

Professor O'Dowd is Professor of Physics and Director of NUI Galway's Centre for Climate and Air Pollution Studies. He has published more than 160 papers (five in *Nature*/*Science*) in Atmospheric Physics and aerosol–cloud–climate interactions and has a h-index of 40. He served as joint editor in-chief of the *Journal of Geophysical Research* (*Atmospheres*) for seven years. In recognition of is research, he has been awarded the Smoluchowski Award for aerosol research, elected Member of the Royal Irish Academy, awarded Doctorate of Science by the University of Manchester, elected Fellow of the Institute of Physics and is Fellow of the Royal Meteorological Society. He has managed research projects worth around 20 M€ to date and currently is serving a third term as co-chair of the International Committee on Nucleation and Atmospheric Aerosols, is a member of the executive committee of the International Association of Meteorology and Atmospheric Science and is ex-offico member of the International Commission on Clouds and Precipitation.

Dr Ruggero Pardi

Dr Pardi is an internationally recognised investigator in the field of integrin biology, and has devoted his scientific career to the study of the pathophysiology of adhesive interactions in the immune system and in the pathogenesis of cancer. He obtained his MD and Specialty Degree in pneumology at the University of Milan in 1980 and 1983, respectively. In 1985 he moved as a post-doctoral fellow to the Department of Pathology, Stanford University School of Medicine, in the group led by E. G. Engleman. Between 1985 and 1988 Dr Pardi pioneered the field of leukocyte–endothelial cell interactions, and was among the first to characterise the cell subsets and molecules involved in the adhesive interactions of various leukocyte subsets with primary microvascular endothelium (*J. Clin. Invest.*, 1987, **79**: 1679). Dr Pardi's group has identified and fully characterised at the genetic and functional level novel intermediates in integrin-generated signals leading to the control of gene expression programs (*Nature*, 2000, **404**: 617) that are dysregulated in precancerous lesions (*Oncogene*, 2008, **27**: 2401; *J. Exp. Med.*, 2008, **205**: 465) His most recent work concerns the demonstration that cooperative and concurrent signalling by chemokines and integrins is crucial to the coordination of the various steps of leukocyte extravasation (*Blood*, 2009, **114**: 1073; *Blood*, 2009, **113**: 1699; *J. Cell Sci.*, 2009, **122**: 268). In the last 20 years Dr Pardi has been awarded numerous grants from national and international funding agencies, and has coordinated several EU-funded networks, including a FP6 Network of Excellence (MAIN: www.main-noe.org) composed of 16 institutes from eight EU and associated countries, focusing on inflammatory cell migration. From 2003 to 2007 he served as Dean of the Graduate School of Molecular Medicine of San Raffaele University. In 2008 he was named Chairman of the Division of Immunology, Transplantation and Infectious Diseases of the Scientific Institute San Raffaele. Overall, he has authored over 80 publications in international peer-reviewed journals, with a global impact factor exceeding 600. He has been invited as a speaker to over 25 international meetings in the last 15 years.

Professor Claude Pichard

A specialist in inner medicine and in gastroenterology, Professor Pichard studied clinical nutrition in the group of Professor K. N. Jeejeebhoy (Toronto, Canada) in the 1980s. After returning to Europe, he became professor of nutrition and set up the division of clinical nutrition of Geneva's University Hospital. Besides clinical activities, he teaches in schools of medicine, sciences and dietetics. His research group is involved in several thematic areas among which are the nutritional modulation of cancer cell growth, the relation between catabolism and chronic diseases, the application of body composition measures, biometrics and the economy of health. Professor Pichard has published more than 380 articles, of which more than 200 are referenced in PubMed, and he has presented more than 350 conferences in national or international congresses. Professor Pichard is active in 24 European and international academic societies. He was chairman of the European Society for Clinical Nutrition and Metabolism (ESPEN) until 2006 and is currently ESPEN's Educational and Clinical Practice Committee course director.

Dr Alessandro Rubinacci

Dr Rubinacci is in charge of the Bone Metabolism Unit of the San Raffaele Scientific Institute, Milan, a translational unit that combines research activity in bone pathophysiology with a clinical service for osteoporosis and metabolic bone and mineral diseases. Dr Rubinacci graduated with honours in medicine (1977) and specialised with honours in orthopaedics and traumatology (1980) at the University of Naples, after which he joined as a postdoc the Orthopaedics Department of the San

Raffaele Scientific Institute, Milan, Italy. He was research fellow (1983) in the McKay Laboratory of the Orthopaedics Department, University of Pennsylvania, Philadelphia, USA, and in the Biochemistry Department of the Catholic University of Leuven, Belgium, (1984–1986). He became established Researcher and Senior Researcher at the San Raffaele Scientific Institute, Milan (1993 to present). Dr Rubinacci has been a visiting researcher at the Marine Biological Laboratory, Woods Hole, MA, and Massachussetts University, Amherst, for collaborative studies. He has obtained awards for his studies and was a member of the Life Science Working Group of ESA (2004 to 2006). He has contributed to international clinical trials for drug development. His scientific interest includes osteoporosis pathogenesis and treatment, bone as an ion exchange organ, the endocrine regulation of osteoblast functions and bone marker development and validation. Research results, reported in 100 full papers, constitute innovative contributions to the pathophysiology of bone and mineral metabolism.

Annex 2: List of some publications produced through the ELIPS programme over the past ten years

Representatives from the ELIPS user community were asked to compile a list of publications related to investigations performed with support from the ELIPS programme over the past ten years. These lists have been assembled and are provided below for reference.

Life Sciences

Astrobiology

- Rabbow, E. *et al.* (2009). EXPOSE – an astrobiological exposure facility on the International Space Station – from proposal to flight. *Origins Life Evol. Biosph.* **39**: 581–598.
- Onofri, S. *et al.* (2008). Resistance of Antarctic black fungi and cryptoendolithic communities to simulated space and Martian conditions. *Studies in Mycology* **61**: 99–109.
- Cockell C.S. *et al.* Exposure of phototrophs to 548 days in low Earth Orbit: microbial selection pressures in outer space and on early Earth. *ISME Journal* **5**: 1671–1682.
- Horneck, G. *et al.* (2010). Space microbiology. *Microbiol. Mol. Biol. Rev.* **74**: 121–156.
- De Vera, J. *et al.* (2010). Survival potential and photosynthetic activity of lichens under Mars-like conditions: A laboratory study. *Astrobiology* **10**: 215–227.
- Olsson-Francis, K. *et al.* (2011). Isolation of novel extreme-tolerant cyanobacteria from a coastal rock-dwelling microbial community using exposure to low Earth orbit. *Appl. Environ Microbiol.* **76**: 2115–2121.
- Olsson-Francis, K., Cockell, C.S. (2010). Experimental methods for studying microbial survival in extraterrestrial environments. *J. Microbiological Methods* **80**: 1–13.
- De la Torre, R. *et al.* (2010). Survival of lichens and bacteria exposed to outer space conditions – results of the lithopanspermia experiments. *Icarus* **208**: 735–748.
- Raggio, J. *et al.* (2011). Whole lichen thalli survive exposure to space conditions. *Astrobiology* **11**: 281–292.
- Bryson, K.L. *et al.* (2011). The ORGAN experiment on EXPOSR-R on the ISS. *Adv Space Res.* **48**: 1980–1996.

Behaviour and Performance

- Hockey, G. R. J., Gaillard, A. W. K., & Burov, O. (eds.) (2003). *Operator functional state: the assessment and prediction of human performance degradation in complex tasks*. Amsterdam: IOS.
- Kanas, N. & Manzey, D. (2008). *Space psychology and psychiatry* (2nd ed.). Dordrecht, The Netherlands: Kluwer.
- Kanas, N., Salnitskiy, V., Grund, E. *et al.* (2000). Interpersonal and cultural issues involving crews and ground personnel during Shuttle/Mir space missions. *Aviation Space and Environmental Medicine* **7**: A11–A16.
- Kanas, N., Saylor, S., Harris, M.A., Neylan, T., Boyd, J., Weiss, D.S. *et al.* (2010). High versus low crewmember autonomy in space simulation environments. *Acta Astronautica* **67**: 731–738.
- Kanki, B., Rogers, D., Bessone, L., Parke, B. Sandal, G.M. & Whitely, Y. (2009). Team performance and space safety. *Journal of the British Interplanetary Society*, **62**: 273–281.
- Palinkas, L. & Suedfeld, P. (2008). Psychological effects of polar expeditions. *Lancet*, 12; 371(9607): 153–63.
- Sandal, G.M. (2004). Culture and crew tension during an International Space Station simulation; Results from SFINCSS'99. *Aviation, Space and Environmental Medicine* **75**(1): 44–51.
- Sandal, G.M., Bye, H.H. & van de Vijver, F.J.R. (2011). Personal values and crew compatibility in a 105 days space simulation study. *Acta Astronautica*. **69**: 141–149. DOI: 10.1016/j.actaastro.2011.02.007.
- Sandal, G.M., Leon, G. & Palinkas, L. (2006). Human challenges in polar and space environments. *Reviews in Environmental Science and Bio/Technology* **5**: 281–296.
- Sandal, G.M. & Manzey, D. (2009). Cultural determinants of co-working of ground personnel in the European Space Agency. *Acta Astronautica* **65**: 1520–1569.

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Biological Effects of Radiation

- Cucinotta, F.A. & Durante, M. (2006). Cancer risk from exposure to galactic cosmic rays: implications for space exploration by human beings. *Lancet Oncol.* 7: 431–435.
- Spillantini, P., Casolino, M., Durante, M., Mueller-Mellin, R., Reitz, G., Rossi, L., Shurshakov, V., & Sorbi, M. (2007). Shielding from cosmic radiation for interplanetary missions: active and passive methods. *Radiat. Meas.* **42**: 14–23.
- Durante, M. & Cucinotta, F.A. (2008). Heavy ion carcinogenesis and human space exploration. *Nat. Rev. Cancer* **8**: 465–472.
- Durante, M. (2008). Physical and biomedical countermeasures for space radiation risk. *Z. Med. Phys.* **18**: 244–252.
- Jakob, B., Splinter, J., Durante, M. & Taucher-Scholz, G. (2009). Live cell microscopy analysis of radiation-induced DNA double-strand break motion. *Proc. Natl. Acad. Sci. USA* **106**: 3172–3177.
- Durante, M. & Loeffler, J.S. (2010). Charged particles in radiation oncology. *Nat. Rev. Clin. Oncol.* 7: 37–43.
- Durante, M. & Bruno, C. (2010). Impact of rocket propulsion technology on the radiation risk in missions to Mars. *Eur. Phys. J.* **D60**: 215–218.
- Ritter, S. & Durante, M. (2010). Heavy-ion induced chromosomal aberrations: a review. *Mutat. Res.* **701**: 38–46.
- Durante, M., Reitz, G. & Angerer, O. (2010). Space radiation research in Europe: flight experiments and ground-based studies. *Radiat. Environ. Biophys.* **49**: 295–302.
- Carpenter, J.D., Angerer, O., Durante, M., Linnarson, D. & Pike, W.T. (2010).Life sciences investigations for ESA's first lunar lander. *Earth Moon Planets* **107**: 11–23.
- Maalouf, M., Durante, M. & Foray, N. (2011). Biological effects of space radiation on human cells: history, advances and outcomes. A general review. *J. Radiat. Res.* **52** 126–146.
- Newhauser, W.D. & Durante, M. (2011). Assessing the risk of second malignancies after modern radiotherapy. *Nat. Rev. Cancer* **11**: 438–448.
- Durante, M. & Cucinotta, F.A. (2011) Physical basis of radiation protection in space travel. *Rev. Mod. Phys.* **83**: 1245–1281.

Bone, Muscle and Exercise

- Rittweger, J., Frost, H., Schiessl, H., Ohshima, H., Alkner., B., Tesch, P. & Felsenberg, D. (2005). Muscle atrophy and bone loss after 90 days' bed rest and the effects of flywheel resistive exercise and Pamidronate: Results from the LTBR study. *Bone* **36**(6): 1019–1029.
- Mulder, E.R., Stegeman, D.F., Gerrits, K.H.L., Paalman, M.I., Rittweger, J., Felsenberg, D. & de Haan, A. (2006). Strength, size and activation of knee extensors followed during 8 weeks of horizontal bed rest and the influence of a countermeasure. *Eur. J. Appl. Physiol.* **97**(6): 706–715.
- Rittweger, J., Winwood, K., Seynnes, O., de Boer, M., Wilks, D.C., Lea, R., Rennie, M.J. & Narici, M. (2006). Bone Loss from the Human Distal Tibia Epiphysis during 24 Days of Unilateral Lower Limb Suspension. *J. Physiol.* **577**(1): 331–337.
- Blottner, D., Püttmann, B., Salanova, M., Schiffl, G., Rittweger, J., Gunga, H.-C., J., Felsenberg, D. & Schoser, B.G. (2006). Skeletal muscle deconditioning, Nitric Oxide (NO) biomarker, and exercise countermeasure – five years of bed rest studies. *J. Gravit. Physiol.* **13**(2): 49–58.
- Rittweger, J. & Felsenberg, D. (2009). Recovery of muscle atrophy and bone loss from 90 days bed rest: Results from the LTBR study. *Bone* **44**(2): 214–224. PMID: 19022418.
- Rittweger, J., Simunic, B., Bilancio, G., De Santo, N.G., Cirillo, M., Biolo, G., Pisot, R., Eiken, O., Mekjavic, I.G. & Narici, M. (2009). Bone loss in the lower leg during 35 days of bed rest is predominantly from the cortical compartment. *Bone* **44**(4): 612–618 PMID 19168165; DOI: 10.1016/j.bone.2009.01.001.
- Rittweger, J., Beller, G., Armbrecht, G., Mulder, E., Buehring, B., Gast, U., Dimeo, F., Schubert, H., de Haan, A., Stegeman, D.F., Schiessl, H. & Felsenberg, D. (2010). Prevention of bone loss during 56 days of strict bed rest by side-alternating resistive vibration exercise. *Bone* **46**(1):137–147. DOI: 10.1016/j.bone.2009.08.051.
- Moriggi, M., Vasso, M., Fania, C., Capitanio, D., Bonifacio, G., Salanova, M., Blottner, D., Rittweger, J., Felsenberg, D., Cerretelli, P. & Gelfi, C. (2010). Long term bed rest with and without vibration exercise countermeasures: Effects on human muscle protein dysregulation. *Proteomics* **10**: 3756–3774. PMID: 20957755.

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- Agostini, F., Dalla Libera, L., Rittweger, J., Mazzucco, S., Jurdana, M., Mekjavic, I., Pisot, R., Gorza, L., Narici, M. & Biolo, G. (2010). Effects of incactivity on human muscle glutathione synthesis by a double-tracer and single-biopsy approach. *J. Physiol.* **588**(24): 5089–5104.PMID: 20962001.
- Belavy, D.L., Bansmann, P.M., Böhme, G., Frings-Meuthen, P., Heer, M., Ritttweger, J., Zange, J. & Felsenberg, D. (2011). Changes in intervertebral disc morphology persist 5 mo after 21-day bed-rest. *J. Appl. Physiol.* **111**(5): 1304–1314. PMID: 21799122.

Cardiopulmonary Physiology

- Eckberg, D.L., Halliwill, J.R., Beightol, L.A., Brown, T.E., Taylor, J.A., Goble, R. (2010). Human vagal baroreflex mechanisms in space. *J Physiol.* 1;588(Pt 7): 1129–38.
- Hemmingsson, T.E., Linnarsson, D., Frostel,l C., Van Muylem, A., Kerckx, Y. & Gustafsson, L.E. (2011). Effects of ambient pressure on pulmonary nitric oxide. *J Appl Physiol.* **112**(4): 580–586.
- Karlsson, L.L., Blogg, L., Lindholm, P., Gennser, M., Hemmingsson, T. & Linnarsson, D. (2009). Venous gas emboli and exhaled nitric oxide with simulated and actual extra vehicular activity. *Respir. Physiol. Neurobiol.* **169**, Suppl 1:S59-62.
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- Kerckx, Y. & Van Muylem, A. (2009). Axial distribution heterogeneity of nitric oxide airway production in healthy adults. *J. Appl. Physiol.* **106**(6): 1832–1839.
- Norsk, P., Damgaard, M., Petersen, L., Gybel, M., Pump, B., Gabrielsen, A. & Christensen, N.J. (2006). Vasorelaxation in space. *Hypertension* **47**(1):69–73. Epub 2005 Nov 21.
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- Van Muylem, A., Noël, C. & and Paiva, M. (2003). Modeling of impact of gas molecular diffusion on nitric oxide expired profile. *J. Appl. Physiol.* **94**: 119–127.

Cell and Molecular Biology/Rodent Research

- Bacabac, R.G., Smit, T.H., Van Loon, J.J., Doulabi, B.Z., Helder, M. & Klein-Nulend, J. (2006). Bone cell responses to high-frequency vibration stress: does the nucleus oscillate within the cytoplasm? *FASEB J.* **20**(7): 858–64.
- Monticone, M., Liu, Y., Pujic, N. & Cancedda, R. (2010). Activation of nervous system development genes in bone marrow derived mesenchymal stem cells following spaceflight exposure. *J. Cell Biochem.* **111**(2): 442–52.
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Neuro-Vestibular

Examples of recent literature. This list is not exhaustive, nor is it necessarily representative of all current space-based experiments in the field of neuroscience.

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Physical Sciences

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Complex Fluids: Foams, Emulsions

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Out-of-Equilibrium Solidification

- D.M. Herlach & D.M. Matson (eds). (2012). Solidification of Containerless Undercooled Melts. Wiley-VCH; ISBN: 978-3-527-33122-2.

- Containerless undercooling of drops and droplets. D. M. Herlach, Institute of Materials Physics in Space, DLR, Köln, Germany.
- Computer aided experiments in containerless processing of materials. R. W. Hyers, University of Massachusetts, Amherst, MA, USA.
- Demixing of Cu–Co alloys showing a metastable miscibility gap. M. Kolbe, Institute of Materials Physics in Space, DLR Köln, Germany.
- Short-range order in undercooled melts. D. Holland-Moritz, Institute of Materials Physics in Space, DLR Köln, Germany.
- Ordering and crystal nucleation in undercooled melts. K. F. Kelton, A. L. Greer, Washington University, St. Louis, MI, USA, and University of Cambridge, Cambridge, UK.
- Phase field crystal modelling of homogeneous and heterogeneous crystal nucleation. G.I. Tóth, T. Pusztai, G. Tegze, L. Granasy, Research Institute for Solid State Research and Optics, Budapest, Hungary.
- Effects of transient heat and mass transfer and competitive nucleation on phase selection in rapid solidification. J. Fransaer, M. Krivilyov, Katholike Universitat, Leuven, Belgium, Udmurt State University, Izhevsk, Russia.
- Containerless solidification of magnetic materials using 25 m drop-tube. S. Ozawa, The Institute of Space and astronautical Science, Sagamihara, Japan.
- Nucleation and solidification kinetics of metastable phases in undercooled melts. Wolfgang Löser, Olga Shuleshova, Institut für Festkörper- und werkstoffforschung Dresden, Germany.
- Nucleation within the mushy-zone. D. M. Matson, Tufts University, Medford, US.
- Measurements of crystal growth velocities in undercooled melts of metals. T. Volkmann, Institute of Materials Physics in Space, DLR Köln, Germany.
- Containerless crystallization of semiconductors. K. Kuribayashi, Shibaura Institute of Technology, Tokyo, Japan.
- Measurements of crystal growth dynamics in glass-fluxed melts. J. Gao, Z. Zhang, Y. Zhang, C. Yang, Northeastern University Shenyang, China.
- Influence of convection on dendrite growth dynamics by AC + DC levitation technique. H. Yasuda, Osaka University, Japan.
- Modelling the fluid dynamics and dendritic solidification in EM-levitated alloy melts. V. Bojarevics, A. Kao, K. Pericleous, University of Greenich, United Kingdom.
- Mesoscopic modelling of dendrite growth in undercooled melts. P. Galenko, S. Binder, G. Ehlen, Ruhr University Bochum, Institute of Materials Physics in Space, DLR Köln, Germany.
- Atomistic simulations of nonequilibrium crystal-growth Kknetics from alloy melts. J. J. Hoyt, M. Asta, A. Karma, McMaster University, Canada; University of California, Berkeley, USA; Northeastern University Boston, US.
- Particle-based computer simulation of crystal nucleation and growth kinetics in undercooled melts. Horbach, P. Kuhn, R. Rozas, University Düsseldorf; Institute of Materials Physics in Space, DLR Köln, Germany.
- Multiscale solidification modelling of EML processed samples. Ch.-A. Gandin, D. Tourret, T. Volkmann, D.M. Herlach, A. Ilbagi, H. Henein, MINES ParisTech, Sophia Antipolis, France; Institute of Materials Physics in Space, DLR Köln, Germany; University of Alberta, Canada.
- Properties of SiGe thermoelectric material solidified from undercooled melt by EML. T. Okutani, T. Hamada, Y. Inatomi, H. Nagai, Yokohama National University, Yokohama; Institute of Space and astronautical Science, Sagamihara; National Institute of advanced Industrial Science and Technology, Yokohama, Japan.
- Quantitative analysis of alloy structures solidified under limited diffusion conditions. H. Henein, A. Ilbagi, Ch.-A. Gandin, University of Alberta, Edmonton, Canada; MINRES ParisTech Sophia-Antipolis, France.
- Univariant and invariant mulitphase solidification in ternary alloys. R. Napolitano, Iowa State University, Ames USA.

Annex 2: **List of some publications produced through the ELIPS programme over the past ten years**

- Solidification of peritectic alloys. K. Biswas, S. Samal, Indian Institute of Technology, Kanpur, India.

Soft Matter

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Annex 2: List of some publications produced through the ELIPS programme over the past ten years

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Space–Atmosphere Processes on ISS

- MUE (Miller-Urey experiment), ASIM (Atmosphere–Space Interactions Monitor), and JEM–EUSO (Japanese Experimental Module-Extreme Universe Space Observatory) teams.

Atmospheric electric discharges:

- Neubert, T. *et al.* (2011). The properties of a giant jet reflected in a simultaneous sprite. *J. Geophys. Res.* **116**: A12329. DOI: 10.1029/2011JA016928.
- Luque, A., *et al.* (2011). Mesospheric electric breakdown and delayed sprite ignition caused by electron detachment. *Nature Geoscience* **5**: 22–25.
- Chanrion, O., *et al.* (2010). Production of runaway electrons by negative streamer discharges. J. *Geophys. Res.* **115**: A00E32. DOI: 10.1029/2009JA014774.

JEM–EUSO UHE Cosmic Rays:

- Casolino, M. *et al.* (2011). *ASTRA* 7(4): 477.
- Supanitsky, A. *et al.* (2011). *Astr. Part. Phys.* **35**(1): 8.
- Santangelo, A. & Petrolini, A. (2009). *New J. Phys.* **11**(6): 065010.
- Takahashi, Y. & JEM–EUSO collaboration. (2009). *New J. Phys.* **11**(6): 065009.

MUE ASIM Astrobiology:

- Kotler, J.M. *et al.* (2011). Analysis of Mineral Matrices of planetary soil analogs from the Utah Desert. *Int. J. Astrobiol.* 10(3): 221–229.
- Ehrenfreund, P. *et al.* (2011). Astrobiology and habitability studies in preparation for future Mars missions: trends from investigating minerals, organics and biota. *Int. J. Astrobiol.* 10(3): 239–253.
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Thermophysical Properties

- Chathoth, S.M., Damaschke, B., Samwerand, K. & Schneider, S. (2008). Thermophysicalpropertiesof Si, Ge, and Si–Ge alloy melts measured under microgravity. *Appl. Phys. Lett.* **93**: 071902.
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- Curiotto, S., Battezzati, L., Johnson, E. & Pryds, N.H. (2007). Thermodynamics and mechanism of demixing in undercooled Cu–Co–Ni alloys. *Acta Mater.* **55**: 6642–6650.
- Sechenyh, V., Legros, J.C. & Shevtsova, V. (2011). Experimental and predicted refractive index properties in ternary mixtures of associated liquids. *J. Chem. Thermodyn.* **43**: 1700–1707.
- Blanco, P., Bou-Ali,M.M., Platten, J.K., de Mezquia, D.A., Madariagaand, J.A. & Santamaría, C. (2010). Thermodiffusion coefficients of binary and ternary hydrocarbon mixtures. *J. Chem. Phys.* **132**: 114506.
- Horbach, J., Das, S.K., Griesche, A., Macht, M.-P., Frohberg, G. & Meyer, A. (2007). Self diffusion and Interdiffusion in Al80Ni20 Melts: Simulation and Experiment. *Phys. Rev. B* **75**: 174304.
- ThermoLab Authors (2008). *High Temperature Materials and Processes* **27**(6): 9 papers.
- RAune, R.E. *et al.* (2005). Thermophysicalproperties of IN738LC, MM247LC AND CMSX-4 in the liquidand high temperature solid phase. International Symposium on Superalloys 718, 625, 706 and Various Derivatives. TMS, Warrendale PA, pp. 467–476.
- Wunderlich, R. *et al.*. (2012). Thermophysical Properties of a Fe–Cr–Mo Alloy in the Solid and Liquid Phase. *Steel Res. Int.* DOI: 10.1002/srin.201100156.

Annex 3: Comments received from the user community representatives

A draft version of the evaluation report was forwarded to the ELIPS user community representatives to provide them with an opportunity to comment and provide further information on the whole draft report and its content.

The expert committee reviewed the 33 comments received. Some (19) were considered valid (in the context of the exercise) and resulted in updating the text; some others (14) were not considered fully suitable for a modification of the report content. For the sake of transparency, those comments that did note resulted in updating the report and the responses from the committee are listed below.

General Comments

Comment received: Committee Statement box – I don't understand why *"…the committee relied on the quality of clustered project presentations … rather than more established and objective key performance indicators…"*. Ideally, the report and recommendations of the committee should have been based on an equilibrated combination of these two sources of information.

Committee response: Key performance indicators were not available in the frame of the evaluation. As an example, the background bibliometric study performed in parallel had not produced its first conclusions when the committee met. Wording has been changed to indicate that the committee did not have access to these indicators.

Comment received: Part 2.1 – Intro. On the statement of ELIPS science being inhomogeneous and not always producing scientific results of the highest international standard: to make correct judgment of this fact it might be worth to state that this is not different from any other research funding, a prediction of success remains always a prediction and the outcome mostly follows a Gaussian function.

Committee response: Of course there is for every funding scheme a spread in the quality of the funded projects, but it appeared clear that the average level of the projects funded within ELIPS was below the average of other research funding schemes. While it also mentions that *"Some experiments have produced results of outstanding quality"*, the statement here is not about the existence of a 'spectrum' as such, but about its average.

Comment received: Part 2.1 - Reaching out to a wider scientific community, Recommendation. To the reader, this recommendation might be perceived somehow contradictory to the recommendation to reduce the number of projects chosen, but attracting new (more) scientists, widening scopes, etc.

Committee response: There may be a misunderstanding here. The issue is not to have a bigger community of users but a more diverse one, i.e. to widen the basis of the community. Selecting fewer experiments would not necessarily be problematic with this recommendation; it is however clear that it will make the competition greater. Wording has been modified.

Comment received: Part 2.2 – Topical Teams. I could suggest additional recommendations with regards to Topical Teams in order to increase their efficiency and their usefulness:

1. The constitution of a Topical Team could be directly proposed by ESA to a scientist or to a group of scientists in order to provide advice on a particular topic. In order to avoid "endogamy" and to enlarge the size of the scientific community interested in or dedicated to space research, the proposal could include the specific request of the recruitment and incorporation of scientists not previously involved in space research activities.
2. Topical Teams could also be used to prepare specific experiment proposals. Several scientists, having presented separately projects or ideas to an AO, could be requested to form a Topical Team (even with the incorporation of new members, either as partners or advisors) in order to elaborate a joint merged experimental proposal.

Committee response: While they are in line with the general approach recommended by the committee (having a more top-down approach), these comments are rather too detailed to be fully discussed at this stage.

Comment received: Part 2.2 – Topical Teams. In regards to the recommendation of "regular review and rotation of Topical Team memberships", rotation and memberships should be defined by the Topical Teams themselves.

Committee response: This could indeed be a sensible way to accommodate the specificities of each TT and the domain(s) it covers. The committee recommends that discussion is opened on how to renovate the TT concept and such input would be valuable in the frame of such a discussion.

Comment received: Announcement and selection of experiments. Announcements of Opportunities (AOs) should contain exhaustive information, as detailed as possible, on the constraints and limitations of the available experiment facilities. Furthermore, AOs could consist of two successive phases or steps:

1. A call for experiment ideas.
2. An evaluation of the similarities and synergies of the ideas proposed by scientific teams in order for them to work together and submit a joint proposal to the AO within clearly defined frames.

(These proposals have been the result of the discussions of a Topical Team on Plant Space Experiments, which is currently active)

Committee response: These comments were not discussed by the expert committee and are rather too detailed to be fully discussed at this stage.

Comment received: Part 2.2 – Announcement and selection of experiments. The committee identifies the importance of ground-based research. It was not discussed but one might even speculate that experiments might only fly when a clear g-response has been demonstrated on ground in microgravity simulators (bed-rest, clinostat, magnet, random positioning machine, etc.) or in hypergravity (centrifuge). This might also increase the success rate of real microgravity experiments, hence increasing the science output of the programme especially dealing with limited flight opportunities.

Committee response: This was not discussed in detail by the expert committee and is rather too detailed to be fully discussed at this stage. Furthermore, the relevance of this comment to physical sciences seems to be lower than for life sciences.

Comment received: Over the years I have seen too often that the choice for a particular piece of hardware is not always based on what is the best for an experiment but is at times chosen for industrial or geo-return reasons. This has to be stopped. That is: when we want to increase and push science output. Maybe a comment can be made on this somewhere.

Committee response: While a salient characteristics of the programme, the issue of geo-return was not highlighted during the consultation and committee discussion; addressing it in the report would require further information and discussion. However, there is no doubt that geo-return would be considered if the recommendation to perform an audit in best practices in hardware development is followed.

Comments on Overarching Life Sciences

Comment received: I recommend including that the success of biological programmes can also be demonstrated by the following ways:

1. ESA should encourage and financially support articles in which results from ESA missions (and others) are presented not as review but rather as presentation of hypotheses originating from the data linkage of (*a*) various disciplines and/or (*b*) various animal models. This idea takes into consideration that any modification of one component of the organism affects other systems of this organism that are not in the focus of the scientist and his often alone-standing study. One example for each of the two approaches will underline the usefulness and necessity of this task.
   a) ad *(a)* In humans, the physiology of the vestibular system is closely linked to the physiology of the cardiovascular system (cf. Pompeiano et al., 2004). Therefore, modifications of the vestibular system affect the cardiovascular system and *vice versa*.
   b) ad *(b)* Based on the comparative approach using results from different animal species, different experimental techniques, different space missions, and different principal investigators, vestibular sensitisation was detected as a mechanism of how organisms adapt to the microgravity environment (cf. Horn, 2008).
2. This ambitious task of finding over-all valid principles from studies in space will clearly demonstrate to which extent the selection of experiments can be justified. The work about the development of such integrative/systemic hypotheses could be organised by the Erasmus Experiment Archive, maybe by contracts with non-ESA employed or retired scientists who are not under the pressure of daily work in the laboratory, preparation of proposals, etc.

Committee response: This was not discussed in detail by the expert committee and is rather too detailed to be fully discussed at this stage. However, the committee specifically recommends to further promote interdisciplinarity in the programme.

Comment received: Second bullet point of the second topic ("Promote interaction between sub-disciplines such as immunology, radiation biology and nutrition…"). This note is in line with the comment above; however only on the experiment performance level and not on the level of developing over-all and integrated hypotheses taking data from all these disciplines.
Committee response: This was not discussed in detail by the expert committee and is rather too detailed to be fully discussed at this stage.

Comments on Microbiology

Comment received: This section is very much focused on yeast (S. *cerevisiae*). There is also a lot of work done on bacteria. Basic science: see work from Leys/Mergeay and technology (ISS fouling e.g. Mergeay et al. or humidity de Goffou et al); human microflora (Welling/Harmsen et al.).
Committee response: The presentation and summary report provided were very much focused on yeast; the text reflects this emphasis.

Comments on Astrobiology

Comment received: Criticisms – It should also say the community should study "The effects of the space environment on active microorganisms and their interactions with substrates".
Committee response: This was not discussed in detail by the expert committee and is rather too detailed to be fully discussed at this stage.

Comments on Plant Biology

Comment received: In the plant section I miss some comments and future perspectives for long duration missions on plants and food production. For this we would, in shorter time scale, require facilities for large plant growth, seeds-to-seeds crop production, etc.
Committee response: This was not discussed in detail by the expert committee and is rather too detailed to be fully discussed at this stage.

Comment received: Future priorities and recommendations – What about seeds-to seeds facilities, crops, etc.?
Committee response: This was not discussed in detail by the expert committee and is rather too detailed to be fully discussed at this stage.

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