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Scientific Perspectives for ESA's Future Programme in Life and Physical sciences in Space

ESSC-ESF Recommendations



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Scientific Perspectives for ESA's Future Programme in Life and Physical sciences in Space

Foreword

The European Programme for Life and Physical Sciences and Applications in Space (ELIPS) was started in 2002, following plans drawn up by the European Space Agency (ESA) in response to scientific developments and after evaluation by the European Space Science Committee (ESSC) and the European Science Foundation (ESF) in 2000. Four years later, ESA has once again asked the ESSC-ESF to evaluate the impact, achievements and opportunities of ELIPS in a prospective manner, with a view to advising the responsible bodies (ESA, Ministerial Council, national agencies) on their future course of action and investments in these areas of research.

Most of ESF's 2000 recommendations concerning the ELIPS programme had been embedded in ESA's final proposal. From ESF's and ESSC's standpoint the most noticeable improvement in the ELIPS programme was the fact that user-defined scientific priorities were feeding the research plan in a bottom-up fashion. At the same time, a top-down strategic framework was defined, stating the broad objectives of ELIPS and the rationale for undertaking specific programmes. This approach is still valid today. Now, as in 2000, ESA should be commended for its support to user-driven research in space and the related opportunities that have been given to European scientists and their international partners to achieve important goals in the disciplines of life sciences and physical sciences. Despite current difficulties in accessing the ISS it is clear that Europe has achieved a leading position in these areas.

The broad user consultations organised by ESSC-ESF in May 2004 have resulted in the publication of strategic, organisational, structural and scientific priority recommendations that are presented and discussed in the main body of the report. This would not have been possible without the very strong commitment and hard work of the Chairs of these workshops, Frances Westall and Gregor Morfill. The unfailing involvement of the Chairs of the thematic sessions, D. Beysens, H.J. Fecht, G. Horneck, M. Lebert, P. Norsk, M. Pages, S. Vitale, D. Weaire, also mandates our gratitude. I would also like to thank all the scientists who have participated to the three workshops, have prepared overview presentations in the various thematic areas, and have contributed to the general discussion leading to the production of this report. Finally N. Walter and J.-C. Worms are to be thanked for the difficult task of managing the organisation of the workshops, drafting the successive versions of the report, and enabling the publication of the final document.

We hope that this report and the recommendations therein will serve as useful guidelines for European research in the future.

Gerhard Haerendel, *Chairman, ESSC-ESF*
Strasbourg, May 2005

Executive summary

Today research in space has become fully embedded in the respective broader fields. It complements ground-based activities and is of a similar scientific standing, as evidenced from the citation impacts (cf § 7.4) which also show that its impact is growing steadily. European scientists and their international partners have achieved important goals in life and physical sciences in space. It is clear that Europe is now in a position to become world leader in some of the areas covered by the ELIPS programme, provided the current support is continued. This report is the product of the ESSC-ESF evaluation exercise of the ELIPS programme (cf. Chapter 1). Chapter 2 provides a synthetic view of the scientific achievements of the ELIPS programme since the year 2000 and presents the recommendations produced by the workshop participants in the various fields of research. More details on those can be found in Chapters 3 and 4. The background behind these findings and recommendations appear in the thematic chapters dealing with physical (Chapter 5) and life (Chapter 6) sciences. The aim of this particular section is to offer a synoptic view of these recommendations, as well as a list of the ELIPS “Cornerstones” defined by the workshop participants.

Strategic recommendations

- Continuation of the ELIPS programme and long-term stability. This can only be attained by a user-driven programme.
- ESA should maintain its efforts to provide access to space for basic and applied research.
- ESA should develop a plan for reliable European utilisation of the ISS. In the event of complete cessation of shuttle flights, ESA should develop alternatives quickly
- Means should be identified and implemented by ESA to strengthen and speed up its “Interim Science Programme”.
- Alternative (to ISS) programme developments should be taken up in the next two years, with the aim of providing a reliable and independent long-term research option for ESA.
- Strategic alliances should be investigated, such as coordinating ground-based and space research, networking, virtual laboratories, etc.
- Research should be better coordinated with national agencies.
- Faster ways of realising ambitious science projects should be studied, e.g. by making use of the modularity of current and planned ISS Laboratories.
- Training and public relations must be continuously improved
- A set of common themes between the areas of physical and life sciences need specific attention and efforts; their scientific cross-cutting character mandate a specific inter-disciplinary approach, along with the inception of specific coordination measures at agency level. These include (i) complex systems, self-organisation, evolution; (ii) dust particle physics; (iii) exobiology; and (iv) preparation of human exploration.

Organisational and structural recommendations

- The current 4-year evaluation period of ELIPS should be kept and synchronised where necessary with important funding decisions; ‘ad hoc’ evaluations of sub-areas should be carried out where necessary.
- The quality of microgravity research must not be judged in isolation but be reflected in complementary ground-based work within the broader context of the “mother” disciplines.
- Research activities in several fields of ESA’s mandatory science programme and of the ELIPS programme would benefit from a closer coordination of efforts.
- Seed-funding for new developments arising out of ELIPS research or MAPs projects must be found, and ESA can help in many ways (e.g. legal, financial, organisational, brokerage etc.).
- The cornerstone structure of ELIPS recommended by ESF in 2000 is still valid today, with several updates to take account of new developments.
- European excellence in space science can be maintained by:
 - ensuring competitiveness, attracting good scientists to the field, facilitating the publication of space science and related ground-based results in high profile (including non-space) journals;
 - an ESA support, coordinated with national efforts, of educational and training programmes in European universities to foster the building of a space-orientated community.

Specific scientific priority recommendations

Fundamental physics

- ESA should support the pre-development of ICAPS and IMPF hardware, including future developments and related ground-based activities, and build the IMPACT facility. Related Phase A studies should be funded for:
 - a “Bose-Einstein Condensate” experiment insert;
 - an insert to study universality concepts near the critical point in liquid complex plasmas.
- Space-borne implementation of experiments in the field of long range quantum communication and quantum entanglement experiments should actively be pursued with, in particular:
 - the development of a multi-purpose drag-free platform to perform these experiments;

- the intermediate implementation of some of these experiments on existing facilities.

Material and fluid physics, interfaces

- Activities of materials / liquid phase physics depend critically on the availability of advanced flight hardware for the ISS (EML, glove box inserts, advanced crystal growth facility, metallic liquids in magnetic fields, new X-ray in-situ diagnostics, etc), accompanied by ground based research in, e.g. synchrotron radiation, neutron scattering, EXAFS.
- Materials physics and fluid physics are closely connected and need close cooperation; two areas of interdisciplinary research have been further defined and could be activated by the formation of two new topical teams, in (a) nucleation, and (b) self-organisation.
- Several new facilities or instruments should be developed to fit the identified programme cornerstones in (a) supercritical chemistry, (b) vibrational physics, (c) combustion research diagnostics tools in parabolic flights and drop-tower facilities.
- For human health and performance and radiation protection issues, studies must be carried out in: accelerator measurements of new materials; multi-functional shielding materials for spacecraft and spacesuit; regolith-based shielding composites; nanomaterials for radiation environment protection; magnetic materials; bonding technologies.

Human and animal physiology

- ESA should ensure that the number of test subjects required by the investigators is obtained, even though the experiments have to be conducted on several space missions.
- The cornerstones have been re-defined and should be supported with (i) facilities which provide access to microgravity, (ii) microgravity simulation studies, (iii) changes in G on the ground and in space, and (iv) animal facilities on the ground and in space.
- ESA should continue to induce spin offs of the results of spaceflight into medical treatment and procedures, development of instruments and equipment, and by using the ISS as a test bed for studying diseases.

Biology

- New facilities are necessary for the future, such as cell culture facilities, bioreactors, standard preservation facilities, quick and deep-freezing facilities in space, advanced microscopy with observation

possibilities of flight samples on ground, automated facilities to support development, growth and harvesting of model systems.

- ESA should encourage that new experiments are performed with established model organisms.
- A Topical Team should be established for addressing questions regarding “How gravity drives evolution” (from simple to complex systems).

Exobiology

- ESA should continue its efforts in exploring Mars.
- Exploring Europa’s sub-ice ocean and its potential for habitability will be another important highlight in exobiology and should be prepared by a study on the habitability of Europa’s oceans and its potential biota.
- ESA should foster its planetary protection activities.
- ESA should provide exposure facilities on the ISS and on autonomous free-flying satellites.
- ESA should consider supporting field studies in regions which are suitable terrestrial analogues of extraterrestrial habitats.

The “Evian” Cornerstones

Life Sciences	Physical Sciences
<p>Biology</p> <ul style="list-style-type: none"> • Molecular and cell biology • Plant biology • Developmental biology 	<p>Fundamental Physics</p> <ul style="list-style-type: none"> • Physics of plasmas and solid/liquid dust particles • Cold atom clocks, matter wave interferometers and Bose-Einstein condensates
<p>Physiology</p> <ul style="list-style-type: none"> • Integrative gravitational physiology • Non-gravitational physiology of spaceflight • Countermeasures 	<p>Material Sciences</p> <ul style="list-style-type: none"> • Thermophysical properties of fluids for advanced processes • New materials, products and processes
<p>Exobiology</p> <ul style="list-style-type: none"> • Origin, evolution and distribution of life • Preparation for human spaceflight exploration 	<p>Fluids Physics</p> <ul style="list-style-type: none"> • Fluid, interface and combustion physics

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Chapter 1: Framework of the study

1.1. Background

At the request of the European Space Agency (ESA), in November 2000 the European Science Foundation (ESF) and the European Space Science Committee (ESSC), organised a workshop in Bischberg (near Strasbourg, France) to evaluate ESA's proposal for a new programme in life and physical sciences in space (ELIPS). This workshop, which gathered some 50 scientists and agency representatives, produced a report which was approved by the Executive Board of ESF, published in early 2001 and sent to the Ministers of ESA Member States in advance of the ESA Ministerial Council of November 2001, during which the ELIPS programme was subsequently endorsed.

Most of ESF's recommendations concerning the ELIPS programme had been embedded in ESA's final proposal. From ESF's and ESSC's standpoint the most noticeable improvement in the ELIPS programme was the fact that user-defined scientific priorities were feeding the research plan in a bottom-up approach. At the same time, a top-down strategic framework was defined, stating the broad objectives of ELIPS and the rationale for undertaking specific programmes.

ESA then asked ESF and ESSC to organise a similar (series of) workshop(s) in preparation of the next Ministerial Council, held in 2004. A large consolidated programme (life and physical sciences in space, Aurora, and possibly other components such as astronomy or Earth observation) will be presented by ESA to the ministers, accounting for roughly 1 billion euros. The science content of such a programme within the existing structure of ELIPS would obviously need to be evaluated independently.

1.2. Objectives and approach

The aim of this exercise was to discuss the expectations and requirements of the user community with regard to a future ESA programme in life sciences (including exobiology), physical sciences (including fundamental physics in space), and general ISS use. The scientific contents of the Aurora programme which are relevant to the ELIPS programme would not be a part of this evaluation exercise, but could become the subject of a separate evaluation by ESF in the near future. The report and recommendations would be made available in September 2005.

A steering group was established, comprising observers from the ESA executive, the Chairman and Executive Secretary of ESSC, ESF Standing Committee representatives (PESC, LESC and EMRC), as well as ESF and ESSC appropriate staff members. This group met twice to prepare the workshop.

The input from ESA consisted in the "skeleton" ELIPS-2 programme.

ESA's research plan in these areas is split into essentially two main categories (life sciences and physical sciences). A two-step approach was followed, in which the workshop itself was split in three parts: one workshop on life sciences, one on physical sciences, and a final workshop to synthesise the findings and recommendations from the first two events. The first round of consultation (the two thematic workshops) took place in Obernai (France) between 5 and 12 May 2004, and gathered a total of some 150 scientists, more or less equally split between the "space" and the "non-space" communities. The balance between disciplines was excellent and allowed an even broader consultation than during the evaluation conducted in the year 2000.

The physical sciences in space category was sub-divided into three general themes: fluid physics, material sciences and fundamental physics. The life sciences in space category was also sub-divided into three general themes: biology, physiology and medical research, *exo/astrobiology*.

A general introduction to each workshop was provided by the organisers, detailing the objectives and expected outcome. ESA also prepared an

Table 1.1. Obernai workshop chairs

Physical sciences workshop Chair: Gregor Morfill	Life sciences workshop Chair: Frances Westall
Fundamental physics Chair: Stefano Vitale	Human and animal physiology Chair: Peter Norsk
Material science Chair: Hans J. Fecht	Biology Chairs: Montserrat Pages, Michael Lebert
Fluid physics Chairs: Daniel Beysens, Denis Weaire	Exobiology Chair: Gerda Horneck

overview of the fields covered, complete with all the relevant information documents. Splinter sessions in each theme identified above took place during roughly half of the workshop. In line with the successful format of the Bischenberg meeting, a chairperson was nominated in each thematic session, with one or two individuals to provide overviews of the theme; in addition, each workshop was chaired by one recognised scientist (Table 1.1). General conclusions for each workshop were prepared during a final plenary session.

At ESA's request, these two workshops looked at the ELIPS programme in a prospective way, namely: What was achieved so far? How should the identified scientific goals evolve in the coming years? What science should be done in the next phase, given the foreseeable schedule, budgetary trend, and institutional framework that Europe will provide for itself. In order to reach a manageable situation in terms of merging and synthesising the information, it was important to assess the scientific contents of ESA's plans by using the same method for each subject. Hence a number of assessment criteria were suggested to the chairs and workshop participants. These suggested criteria are listed below, although it should be pointed out that the participants could decide whether or not to use them, produce new ones, or proceed differently.

1.2.1. General assessment criteria

- Is the strategy effectively based on user/science demands?
- Are the objectives well defined, do they represent scientific needs and incorporate long-term value?
- Flexibility: Does the strategy incorporate the appropriate means to efficiently incorporate new ideas and themes? Is there a need for a top-down approach to develop strategies in Europe, in addition to the science plans?
- European dimension: How well is the strategy connected with general research priorities/programmes in Europe?
- European competitiveness: How well does the strategy strengthen/support European excellence?
- International cooperation: To what extent/in what field can we benefit from cooperative programs/projects with, Japan, Russia and the USA?
- Interdisciplinary cooperation: In what fields is interdisciplinary cooperation wanted/mandatory?
- Implementation: What steps should be taken to realise the Strategy?

1.2.2. Thematic assessment criteria

- Completeness: Are the essential elements reflected in the strategy?
- Maturity: What is the state of development of this field, what is its potential to grow?
- Enabling research: What research activities and technological development are necessary to allow the development of this field?
- Constraints: What would be the main constraints with regards to scientific achievements?
- Cross-fertilisation: What relations should be established with other disciplines in space research and non-space research?
- Approach: How can the objectives be best reached?
- What is the application potential?

1.3. Workshop participants

The participating scientists were key elements of this evaluation. They were composed of “space scientists” (scientists regularly involved in space projects, including ground-based/laboratory experiments) and “non-space scientists” (scientists who were not actively and regularly engaged in space projects). It is important that the participants’ scientific expertise and knowledge in their specific domain are well assessed and recognised within the scientific community. As stated above, the workshops attracted roughly half space scientists and half of non-space scientists. Concerning the latter, the aim of having such mainstream scientists was to provide us with a fresh outlook on those space activities which had to be evaluated. For example, biology projects undertaken in space or using space tools/assets should be evaluated in contrast to other biology projects not using space, to assess their relevance and interest to the whole field; also, the need for space tools had to be demonstrated vis-a-vis other means available to the community. This is the way that ESA is performing its review of proposals, and it is really the only way to do it, to avoid self-replication of research programmes.

The scientists were proposed by:

- the Steering Group
- ESF’s Standing Committee members (PESC, LESC, EMRC)
- ESF’s Expert Committee members (ESSC, European Polar Board, ESF’s Marine Board)
- the European Space Agency; PB-HSR delegates

A complete list of all workshop participants, workshop and session Chairs, presenters, observers, is provided in the appendix section at the end of the report.

1.4. Deliverable

A final meeting took place in Evian (France) on 14 and 15 June 2004, grouping some 30 people. The composition of this particular workshop included the chairs of the thematic workshops, ESSC and ESF staff and experts, ESA observers, and a few additional external experts with both space and non-space expertise, and who had not participated in the first two workshops. The Evian workshop summarised the conclusions and findings of the first workshops, and extracted recommendations.

This report went through the normal approval cycle of all ESF reports. It was thus discussed and approved by the Executive Board of the European Science Foundation at its meeting on 17 November 2004.

Chapter 2: Results of the evaluation of the ELIPS Programme

2.1. Preliminary remarks

The European programme for life and physical sciences and applications using the International space Station, (ELIPS) was started in 2002, following plans drawn up by European Space Agency (ESA) in response to scientific developments and after evaluation by the European Science Foundation (ESF) in 2000. Now, almost four years later, the time has come to evaluate the achievements and to assess, in a prospective manner, the opportunities and impact of ELIPS – with a view to advising the responsible bodies (ESA, Ministerial Council, national agencies) on their future course of action and investments.

The European Space Agency is to be commended for its support of user-driven research in space and the opportunities that have been given to European scientists and their international partners to achieve important goals in the disciplines of life sciences and physical sciences. It is clear that Europe now has a leading position in these areas. ESA has contributed to the success of European excellence in the field of research in space by:

- its support to the ELIPS programme;
- the excellence of the peer reviews of responses to announcements of opportunities;
- the fostering of networking between interdisciplinary Topical Teams;
- communicating the scientific results of research in space; for example through the Erasmus Experiment Archive, and through ESA's own website.
- the public relations activities, which have reached many members of the public.

2.2. The major scientific achievements

Although the unfortunate accidents of the Columbia shuttle and FOTON M-1 mission have led to significant retardation in flight opportunities for a number of programmed experiments, exciting results have been obtained from those experiments that have flown. On the positive side, the flight delays have also provided an opportunity for the provision and development of new facilities.

2.2.1. Physical sciences

The ELIPS programme and research in space play a vital role in the quest for knowledge and our desire to look beyond current frontiers. Advances in the basic understanding of the properties of matter, the laws of interaction forces, etc. ultimately lead to economic benefits, when one considers that nearly 40% of today's economy is based on quantum mechanics and that the application of Einstein's theory of relativity can now be bought in supermarkets in packaged navigation devices. Similar developments will happen as a result of progress in other areas of fundamental physics research.

Some recent highlights or achievements of fundamental physics, materials physics and fluid physics, are summarised hereafter.

2.2.1.1. Fundamental physics

• *Fundamental interactions and universal theories*

- The importance and the impressive developments in the field of long-range quantum communication and entanglement experiments, aimed at assessing the space-time structure of the principles of quantum measurements, are fully recognised.
- In the field of precision measurements that require a more demanding performance of cancellation of gravitational field, the Bischenberg¹ workshop participants recognised the very high scientific potential of some of the measure-

1: ESF-ESSC workshop to evaluate ESA's proposal for a new programme in life and physical sciences in space; November 2000, Bischenberg, near Strasbourg, France.

ments; for example, equivalence principle measurements on atomic and sub-atomic systems, or the search for long-range interactions required by quantum gravity.

- **Complex plasmas**

- Coalescence of complex plasma “fluid drops”. An experiment performed on the International Space Station (ISS), shows the deformation on approach due to a plasma sheath forming on the surface of the complex plasma cloud, despite its extreme porosity (99%).
- Self-organisation of counterstreaming complex plasmas. In normal plasmas one would expect the free energy due to the streaming to lead to instabilities which randomise the particle flow. In strongly coupled systems (experiment performed in parabolic flights) the flow self-organises into discrete interpenetrating streams, which seems to be energetically most favoured.
- The field of “complex plasmas” benefits from a working laboratory on the ISS since 2001 (PKE-Nefedov). Discoveries include the physics of discharging of plasmas and a new charge-induced runaway coagulation (gelation) transition that exceeds the well-known geometric rate by five orders of magnitude.

- **Condensed matter (universality and scaling)**

Phase transitions appearing through manipulation of parameters show universality and a certain scaling behaviour. This universal, scaled behaviour depends only on the space dimensionality D (generally 3, or 2 for surface phenomena) and the dimensionality N of the order parameter (which breaks its symmetry at the transition). The couple (N, D) defines universality classes. The case $N=1, D=3$ corresponds to the gas-liquid critical point, where outstanding results have been obtained thanks to the space conditions of weightlessness.

2.2.1.2. Physics of fluids and interfaces

- **Granular matter**

Observation of a clustering transition in granular matter under vibration, which can be put in relation to the accretion of matter in the cosmos (published in *Physical Review Letters*, commented in *Science* and *Nature*; bronze medal of CNRS).

- **Near-critical fluids**

The microgravity environment of an orbiting platform is ideal for the study of compressible near-critical fluids. In particular, it has permitted the discovery of the Piston Effect, a very efficient way to thermalise such systems (French Academy of sciences award).

- **(Metallic) foam dynamics**

The 2001 Edmond Brun Prize was awarded by the French Academy of Sciences for scientific achievements on foam dynamics. Foams and emulsions have properties largely governed by the surface tension associated with the interface between the two phases, but gravity intervenes to cause drainage and separation in most cases. One particularly interesting case is that of metal foams which usually collapse before solidification in the terrestrial environment. Thus foams of remarkable structure and strength can be demonstrated under low gravity conditions.

2.2.1.3. Materials physics

- **Solidification and casting**

The specific environment of microgravity that can be achieved over long periods on board the ISS provides experimenters with a unique and valuable complementary way to get rid of the complex distorting effects of fluid flow driven by buoyancy in liquid and gas phases. In this way the unambiguous benchmark data needed to discriminate sound three-dimensional models within the diversity that is proposed for solidification and casting processes can be obtained.

- **Materials processing**

Europe has a strong and leading role in the field of materials science and engineering in general and, in particular, constructing complex and multi-functional space equipment, and conducting scientific analysis of materials processing in space and new materials for space.

- **Metallic melts**

High-precision measurements on chemically highly reactive melts at the temperatures of interest require the application of containerless processing, using non-contact diagnostic tools to achieve an accurate surface nucleation control and synthesis of materials free of surface contamination. Based on recent experience in space shuttle and parabolic flight experiments, electromagnetic levitation including sophisticated analysis tools has been developed and established as a versatile and reliable technique in studying highly reactive metallic melts.

2.2.2. Life sciences

The last few years of space experiments have made important contributions to our understanding in the fields of human and animal physiology, biology and exobiology. Exobiology especially has seen an exponential increase in scientific and public awareness

that has led to a corresponding growth of research in space.

2.2.2.1. Human and animal physiology

• *Cardiopulmonary physiology*

- The development of hypertension is now better understood as a result of the experiments undertaken on the ISS. These experiments brought new understanding of the mechanisms for adaptation to weightlessness of the human cardiopulmonary system and the renal control of fluid and electrolyte balance, showing that they are due to both the abolition of hydrostatic pressure gradients in the circulation as well as to a decrease in interpleural pressure.
- Space experiments also led to a discovery that has implications for the positioning of patients with cardiovascular disease. The results show that gravity affects the cardiovascular system in a front to back direction and vice versa in horizontal humans.

• *Bone and muscle*

- Striking interindividual variations in bone-loss responses seem to suggest a need for adequate crew preselection. Targeted treatment or prevention strategies would be useful, not only for space purposes but also for the increasing number of osteoporotic patients on Earth.
- Space missions are an ideal test-bed for the development of countermeasures. This is certainly valid for any bone and muscle loss induced by immobilization. Even for postmenopausal women and or ageing people (female and male) where the cause of bone loss might be different from disuse, these countermeasures would be of high value.

• *Neuroscience*

Implications for long-term exposure to space conditions come from the demonstration that prolonged microgravity during orbital flight modifies the otolith inputs and determines the extent of their contribution to the vertical vestibulo-ocular reflex and optokinetic nystagmus. Recent space studies have demonstrated that the central nervous system is using an internal representation of gravity for the guidance of eye and body movements, for spatial orientation, and for higher cognitive processes.

2.2.2.2. Biology

• *Molecular and cell biology*

Recent studies in microgravity and hypergravity concentrated on the cytoskeleton and signal transduction chains, as they control fundamental cellu-

lar functions, such as maintenance of cell architecture, cell motility, cell division, regulation of enzymes, ion channels and gene expression.

With regard to understanding human health issues on long-term space flights; for example, depression of the immune system or the induction of cancer, recent studies in microgravity and hypergravity are providing understanding of the mechanisms by which cellular systems sense the absence of gravity and by which many functions in humans, such as bone development, heart function and immunocompetence, are altered.

• *Plant biology*

Major progress has been made in understanding how gravity is sensed on the cellular level. Experiments using the higher plant *Arabidopsis* have demonstrated the physiological and molecular basis of root gravitropism. Furthermore, for the first time, experiments with single cells (*Chara* and *Euglena*) have allowed the elaboration of a plot of the path for gravity sensing from simple to complex systems to be made.

• *Developmental biology*

Observations of relevance to both extraterrestrial colonisation as well as to biological development on Earth were obtained from space experiments involving fish and amphibians. They revealed critical periods of extremely high sensitivity to altered environmental conditions for the development of the vestibular system.

2.2.2.3. Exobiology

• *Exobiology packages for exploration science missions*

- The Mars Express mission is already providing much data on the geology, climate, and the radiation environment required for assessing its past and present habitability. The finding of methane in the atmosphere of Mars by Mars Express may be relevant to the search for life.
- The Cassini-Huygens space craft to Saturn and Titan is already providing new, exciting data regarding Saturn and the nature of its rings, as well as the first images of the surface of cloud-covered Titan and information regarding the composition of the atmosphere.
- The STONE-1 experiment showed that sedimentary rocks (Mars analogues) embedded into the ablative heat shield of the recoverable capsule of the Foton-12 spaceflight mission could survive terrestrial atmospheric entry.
- The BIOPAN mission demonstrated the survival of micro organisms in space conditions (protected

by either a mineral layer or layer of dead cells). Circularly polarised solar radiation also induced chirality changes in prebiotic molecules.

- For 2011, a Mars sample return mission is planned. The critical health issues in connection with human missions to Mars have been assessed in the HUMEX study by ESA (ESA 2003).

- **Outreach and education**

ESA has established the Virtual Institute of Exobiology at ESA/ESTEC (<http://www.spaceflight.esa.int/exobio>) thereby providing a platform for communication, training and education in the field of exobiology. This virtual institute also hosts the web page of the European Astrobiology Network Association (EANA) a network that currently links scientists active in exobiology from 17 European nations.

- **Internal structure of ESA**

Several steps have been taken by ESA towards maintaining European competitiveness in the rapidly emerging field of exobiology with the preparatory phase of the Aurora programme and its Exploration Programme Advisory Committee.

2.3. Recommendations

The recommendations that are summarised here are discussed and justified in detail in the main body of the report. They are organised in the following way:

- strategic recommendations
- organisational and structural recommendations
- scientific priority recommendations.

2.3.1. Strategic recommendations

- The ELIPS programme should be continued. Long-term stability is of paramount importance in research of this kind. Establishment of a mandatory programme in these research areas should be discussed for the mid-term future.
- Many research areas need access to space to make major new advances possible, or to complement ground-based research. ESA should maintain its excellent efforts to provide access to space for basic and applied research.
- The ISS, and in particular the Columbus module, is the most important laboratory for the midterm future; ESA should develop a plan for reliable European use and pursue its implementation with the other ISS partners. In the event of complete cessation of shuttle flights, ESA should develop alternatives quickly – either European or joint European/Russian utilisation plans.

- Since the research possibilities on the ISS are currently limited, means should be identified and implemented by ESA to strengthen and speed up its interim science programme, wherever possible.
- Since the ISS life-time for research appears to be limited, and since alternative programme developments take time, such developments should be taken up in the next two years, with the aim of providing a reliable long-term research independent option for ESA.
- Strategic alliances should be investigated, such as coordinating ground-based and space research (possible partner – European Union/Commission), networking, virtual laboratories combining European research activities using, for example, grid-technology etc.
- Research should be better coordinated with national agencies on the programmatic level as well as on the utilisation level (the latter especially for an efficient use of the facilities).
- Faster ways of realising ambitious science projects should be investigated and studied (Phase A), for example, by making use of the modularity of current and planned ISS laboratories.
- Training and public relations must be continuously improved; for example by press releases and high quality professional television documentaries.
- The establishment of Cornerstone Institutes (CIs) was suggested during the workshops. Means to develop such institutes in a flexible manner, i.e. with due regard for the evolutionary aspect of the ELIPS cornerstones, could be discussed by ESA and Programme Board delegates. The aim of these CIs is to gather European representation in the given fields, monitor on-going projects, enlarge the contacts with non-space specialists; national agencies should be represented in the CIs.

2.3.2. Organisational and structural recommendations

- The evaluation period of ELIPS by the ESF, currently four years, should be kept and synchronised where necessary with important funding decisions.
- Ad hoc evaluations of sub-areas should be carried out where necessary.
- The quality of microgravity research must not be judged in isolation, but be reflected in complementary ground-based work within the broader context of the parent disciplines. Future evaluations should take this into account – especially in the light of some of the strategic recommendations made above.
- Research activities in the different fields of space

science (including astronomy) and research in space (as exemplified by the ELIPS programme) would benefit from a closer coordination of efforts. The appropriate organisational steps should be developed and implemented by ESA.

- Seed-funding (or venture capital) for new developments arising out of ELIPS research projects must be found, if the added value to the community is to be realised properly. ESA can help in many ways (for example legal, financial, organisational, brokerage etc.), even within its current statutes, and ways to optimise this should be constantly addressed.
- The current cornerstone structure of ELIPS, as recommended in 2000, is still basically as valid today as it was then, although it had to be updated to take account of new developments. This is always necessary in rapidly evolving fields, and is a healthy sign.

2.3.3. Common scientific priority recommendations (life and physical sciences)

Generally, the existing and planned facilities should be used (or brought into use) as quickly as possible to get the maximum scientific return. The decisions taken recently by the US in the context of research on the ISS provide some constraints, but also some great opportunities for Europe.

On the other hand, the continued doubts about the access and availability of the ISS due to the shuttle uncertainties have already started to hurt some research programmes, in particular the Microgravity Application Programme (MAP), where the industrial partners are beginning to doubt the benefits of application-related studies under reduced gravity, because these are not taking place, and the academic teams are not getting the scientific return essential to ensure continuity of funding. This harbours the great danger that, in spite of the great attraction of opportunities offered by research in space, the know-how and, more especially, young scientists, are lost to the field.

Thanks to the interim programme of ESA, some access to space will exist now in the short term (sounding rockets, Foton flights, Microgravity Science Glovebox inserts, Russian ISS module) and this is extremely important. It is also important to demonstrate that ESA is determined to seize the fresh opportunities for research in space, by developing – from the interim programme – a clear roadmap for future use of the ISS and beyond.

For full exploitation of the research, the take-up

of opportunities offered by the space exploration initiative is an imperative goal. In order to reach this goal, the physics and life sciences disciplinary groups jointly suggest the following recommendations to ESA:

- In order to continuously improve European excellence in space science, ESA should emphasise that space experiments must be embedded in strong basic science in the applying laboratory. This can be attained only by a user-driven programme.
- European excellence in space science can be maintained by:
 - ensuring competitiveness and by attracting good scientists to the field. ESA can play an effective role by investigating ways of facilitating the publication of space science results and results from related ground-based studies in high profile journals, including non-space journals;
 - ensuring that equipment used for research in space is regularly updated (for example, modular facilities/laboratories) and that the conditions in space are correctly controlled;
 - ESA support of educational and training programmes (for example, PhD, Marie-Curie etc.) at European universities to foster the building of a space-orientated community. In this area, coordination of ESA's efforts with national efforts is mandatory.
- Space science relies more and more on transdisciplinary approaches to a research subject; for instance the human exploration of the solar system. ESA should foster collaboration and networking on a European and international basis; for instance through continued support of the Topical Team programme, coordinating it with the other relevant ESA directorates.
- Ideally, ESA should programme more announcements of opportunities, (AOs), for flight opportunities, for example at least once a year, although it is recognised that this is dependent upon the availability of flight opportunities and/or carriers.
- To ensure the highest quality science, ESA should conduct or instigate more frequent, rigorous evaluation of the scientific results of completed space missions.
- The Obernai workshop participants have identified a set of common themes between the areas of physical and life sciences. These areas, detailed hereafter, need specific attention and efforts on behalf of the scientific community and of ESA. They are not just structural or procedural issues, but their scientific cross-cutting character mandates a specific interdisciplinary approach,

along with the inception of specific coordination measures at agency level.

- complex systems, self-organisation, evolution
- dust particle physics, exobiology
- preparation of human exploration (fluid and material sciences)
- general diagnostics.

2.3.4. Specific scientific priority recommendations

2.3.4.1. Physical sciences

• *Fundamental physics*

The recommendations in this area focus in particular on the future IMPACT facility to be installed on board the ISS, and also on foreseen developments in the areas of cold atom physics, Bose-Einstein condensates, equivalence principles, quantum entanglement. Indeed, equivalence principle experiments, antimatter gravitational properties, matter-wave interferometers, are examples of experiments that need extreme free-fall conditions that can be achieved only in space. Space environment conditions can be achieved with a variety of techniques; for those experiments where repeatability and modularity are a key issue, ISS is a most suitable platform.

- The fundamental physics IMPACT facility should be built by ESA.
- To prepare this era of use, ESA should support the predevelopment of ICAPS and IMPF hardware for the IMPACT facility, support parabolic flight campaigns for PK and ICAPS precursors, and build the IMPF precursor experiment PK4. In addition the use of PK3+ in the interim science programme should be supported.
- A virtual laboratory network for IMPACT-related research should be set up.
- Concerning future developments when this facility is in place, it is strongly suggested that a Phase A study be funded for a Bose-Einstein condensate experiment insert in the IMPACT facility. A Phase A study for investigating an IMPACT insert for studying universality concepts near the critical point in liquid complex plasmas should also be financed.
- Possibilities to use the long-term free-fall conditions of space to reach femto-Kelvin temperatures should be investigated.
- In the field of long-range quantum communication and quantum entanglement experiments, aimed at assessing the space-time structure of the principles

of quantum measurements, it is strongly recommended that the substantial leap in the scale of these experiments which would be allowed by a space-borne implementation, is actively pursued.

- In the field of precision measurements requiring a more demanding performance of cancellation of gravitational field, it was also strongly recommended to actively explore:
 - the possibility of developing a multipurpose drag-free platform to perform these experiments;
 - the intermediate implementation of some of these experiments on existing facilities as an enabling step toward the final experiment on such a drag-free platform.

• *Materials physics and physics of fluids and interfaces*

- The number of flights needs to be increased and existing programmes continued, including the facilities for Columbus. All activities of materials/liquid phase physics depend critically on the availability of advanced flight hardware for the International Space Station, such as electromagnetic levitation facilities (EML), Glove box inserts; advanced crystal growth facility; metallic liquids in magnetic fields; and new X-ray in situ diagnostics.
- The research conducted in microgravity must be accompanied by ground-based research looking into structural arrangement by, for example, synchrotron radiation, neutron scattering, EXAFS, etc.
- Beyond the cornerstones first defined at the Bischenberg meeting, and updated at the Obernai workshop², one should study: (1) thermophysical properties for the analysis of casting processes and to develop a theory of high-temperature melts; and (2) material design from fluids. In the area of physics of fluids and interfaces, two sub-topics are considered priority themes to be studied: (1) high-pressure and supercritical combustion and (2) boiling and boiling crisis.
- Materials physics and fluid physics are closely connected and this clearly implies a close cooperation between these communities and, to some extent, with the fundamental physics community. Two areas of interdisciplinary research have been further defined for the future and could be activated by the formation of two new topical teams:
 - *Nucleation*: bridging the activities in metallic materials to more complex systems, such as

2: The second ESF-ESSC thematic workshop, held at Obernai, near Strasbourg, France, 5-12 May 2004.

proteins, semiconductors, complex macromolecules.

- *Self-organisation*: This feature is encountered in systems far from the thermodynamic equilibrium. During this process spontaneous structure formation can occur, driven by external or internal forces.
- Concerning the Electro-Magnetic Levitator (EML), experiments to be performed are:
 - 1g EML: high flow velocity dominated by large magnetic fields
 - 1g EML: low flow velocity dominated by Marangoni convection due to laser heating
 - microgravity EML: wide range of fluid flow conditions from 0.1 cm/s to 18 cm/s due to quasi-static acceleration levels and controllable magnetic fields; heat flow determined by radiation due to containerless processing in UHV.
- Several new facilities or instruments should be developed to fit the identified programme cornerstones; these encompass:
 - a facility for supercritical chemistry
 - a facility supporting investigations in vibrational physics
 - advanced diagnostics to support combustion research in ground-based free-fall facilities (parabolic flights and drop-tower).
- Human health and performance issues, radiation protection issues (radiation exposure and mission requirements, radiation measurements technologies, shielding solutions etc) are paramount. Hence, studies concerning the following topics must be carried out:
 - accelerator measurements of new materials
 - multifunctional shielding materials for spacecraft and spacesuits
 - regolith-based shielding composites
 - nanomaterials for radiation environment protection
 - magnetic materials
 - bonding technologies (brazing, welding, self-healing).

2.3.4.2. Life sciences

- *Human and animal physiology*
- ESA should facilitate the development of the necessary hardware for accepted experiments; ensuring that proposals should not be limited by what is already available. In this way, scientific excellence will not be sacrificed for temporary technical reasons.
- To obtain as high a scientific quality as possible, ESA should make sure that the number of test

subjects required by the investigators is obtained, even though the experiments have to be conducted on several space missions.

- It is suggested that the cornerstones from the Bischenberg meeting be restructured so that they better fit the more applied aspects of the future exploration/manned space programme. The suggested new cornerstones are therefore:
 - *Integrative gravitational physiology*: To explore in an interdisciplinary way systems that are sensitive to gravity, such as (but not limited to) the: cardiovascular system, pulmonary system, nervous system, fluid-electrolyte homeostasis, skeletal system, muscular system, immune system etc.
 - *Non-gravitational physiology of spaceflight*: Exploring effects of the non-gravitational extreme environments of space such as (but not limited to): nutrition, radiation, isolation, confinement, noise, disruption of circadian rhythms, immobilisation, hypobaric conditions (for example extravehicular activity, EVA), etc.
 - *Countermeasures*: Developing physiological, pharmacological, psycho-logical, and mechanical countermeasures against (but not limited to): spatial disorientation (nausea, imbalance), orthostatic intolerance, bone loss and microarchitectural deterioration, muscle atrophy and weakness, cardiac atrophy, radiation, nutrition etc.
- In addition, it is suggested that the three cornerstones be supported with facilities that give access to microgravity (parabolic flights, ISS, taxi flights), microgravity simulation studies (bed rest, water immersion etc.), changes in gravity on the ground and in space (centrifugation, short arm-centrifuge etc.), and animal facilities, also on the ground and in space.
- Encouragements to scientific users: Scientists are encouraged to:
 - be interdisciplinary in their approach.
 - explore differences between individuals
 - conduct comparisons with clinical (pathophysiological) conditions
 - be aware of the fact that astronauts represent a highly selected group of individuals
 - conduct gender comparisons
 - perform interspecies comparisons.

ESA should continue through the MAPs to induce spin-offs of the results of spaceflight into medical treatment and procedures, development of instruments and equipment etc. by using the ISS as a test-bed for studying diseases.

- **Biology**

- Apart from the existing or facilities planned for the near future, some new facilities are necessary, such as cell culture facilities, different kinds of bioreactors, standard preservation facilities, a quick and deep-freezing facility in space for the emerging high-throughput technological approaches, advanced microscopy with observation possibilities for flight samples on the ground, NIZEMI (upgrade to fluorescence techniques) and automated facilities to support development, plus growth and harvesting of model systems are required to accommodate the needs of the growing number of promising new research lines. In addition, ground-based facilities should be increased (for example, RPMs at each USOC). For a better understanding of the additional (besides micro-gravity) influence of space radiation on model systems, access to accelerators and strong radiation sources is required.
- ESA is asked to modify some of the cornerstones in order to adapt to new developments in the last couple of years:
 - Biotechnology should be changed to *Molecular and cell biology* (including the understanding of the impact of gravity on the cellular and molecular level).
 - The cornerstone Plant Physiology should be renamed *Plant biology* indicating the importance of cellular and molecular approaches.
 - The cornerstone Cell and Developmental Biology should be renamed *Developmental biology*. Understanding the impact of gravity on developmental processes is the main scientific target in this research area.
- ESA should encourage new experiments, whenever possible to be performed with established model organisms to enhance the gain of molecular information.
- A topical team should be established for addressing questions regarding how gravity drives evolution (from simple to complex systems).
- ESA is advised to require that all scientists involved in space experiments supply all relevant literature references and hardware description materials in their publications. This initiative should also incorporate information on the Russian-driven experiments and results.

- **Exobiology**

- ESA should continue its efforts in exploring Mars, which is considered a strong candidate for the detection of signatures of life beyond the Earth. ExoMars with its proposed Pasteur payload and the three research goals (search for past life, search for present life, and hazards to humans) should ideally be the next step in this direction.
- Exploring Europa's sub-ice ocean and its potential for habitability will be another important highlight in exobiology. As a preparatory step, ESA should initiate a study on the habitability of Europa's sub-ice oceans, its potential biota and a suitable mission scenario.
- The abovementioned activities to search for signatures of life on other planets and bodies of our solar system must adhere to strict planetary protection rules. Therefore ESA should foster its planetary protection activities.
- ESA should further foster exobiological research in Earth orbit by providing exposure facilities on the ISS and on autonomous free-flying satellites. Amendments of future facilities should include the provision of a sun-pointing device and temperature control that maintains sub-zero temperature during sun exposure.
- Concerning the preparation of human exploratory missions, ESA should foster interdisciplinary cooperation within the ELIPS programme and with its other relevant programmes. Contributions by the astrobiology and planetary exploration discipline include the development of life support systems including bioregenerative approaches; the detection, control and prevention of microbial contamination, and investigations of the radiation field in space and its biological effects. The studies require preparatory robotic space missions, use of the ISS, as well as supportive ground-based studies.
- ESA should continue supporting research using ground-based facilities to gain information required for designing appropriate search-for-life experiments on Mars and Europa, and to elucidate potentially important pathways of prebiotic synthesis.
- ESA should consider supporting field studies in regions which are suitable terrestrial analogues of extraterrestrial habitats. This will allow the testing and validation of sensitive detection devices for signs of past and present life in preparation for life-detection experiments on Mars and Europa and to train technicians and scientists involved in future planetary missions.

2.4. The Evian³ cornerstones

Cornerstone for materials science

In order to achieve the major goals set within the current programme two cornerstones have been identified:

- **Thermophysical properties of fluids for advanced processes**

Thermophysical properties of fluids for advanced purposes that are required as input parameters for adequately describing balances in volume phases (heat, chemical species, momentum etc.) and at interfaces (solid-liquid, liquid-gas, etc.).

Beyond this cornerstone: Thermophysical properties to analyse casting processes and develop a theory of high temperature melts (elementary, binary, multicomponent, industrial).

- **New materials, products and processes**

In order to develop new materials with particular functionalities and, as a result, new products, new or improved processing techniques are generally required; in particular, for the reliable processing of liquid complex alloys.

Beyond this cornerstone: Materials design from fluids, which is an excellent process, since it is very flexible; the previous cornerstone title was too broad as almost everything could be included in that topic.

Cornerstone for fundamental physics

- The fundamental physics disciplinary group propose to reformulate the first cornerstone of the field of fundamental physics as the *Physics of plasmas and solid or liquid dust particles*, with an emphasis on self-organising aspects and the driving forces behind them.
- The fundamental physics disciplinary group recognises that the scientific case and the technical readiness of experiments on *cold atom clocks, matter wave interferometers and Bose-Einstein condensates in extreme conditions on the ISS* deserve the status of a cornerstone within ELIPS. These experiments will also constitute enabling steps for more ambitious ones, such as Hyper missions, that are already included in the ESA planning at large.

Cornerstone for fluid physics

- Interfaces should be given more prominence in the revised title for this area (*Fluid, interface and combustion physics*).

Cornerstone for biology

- *Molecular and cell biology:* Understanding the impact of gravity at the cellular and molecular levels.
- *Plant biology:* Understanding the impact of gravity on plant systems. Study mechanosensory elements involved in mechanisms of graviorientation and gravishaping.
- *Developmental biology:* Understanding the impact of gravity on developmental processes.

Cornerstone for physiology

- *Integrative gravitational physiology:* Explore in an interdisciplinary way systems which are sensitive to gravity.
- *Non-gravitational physiology of spaceflight:* Exploring effects of the non-gravitational extreme environments of space.
- *Countermeasures:* Developing physiological, pharmacological, psychological, and mechanical countermeasures.

Cornerstone for exobiology

- *Origin, evolution and distribution of life:* Survivability of organisms under extreme conditions on Earth, in space and in (simulated planetary environments).
- *Preparation for human planetary exploration:* Quantify effects of radiation doses and investigate impact of isolation in high stress environments on humans; develop database for identification and use of in situ resources; study life support for long-duration planetary missions.

3: Final ESF-ESSC meeting in Evian, France on 14 and 15 June 2004.

Chapter 3: Progress through the ELIPS programme

3.1. Physical sciences

3.1.1. Fundamental physics

3.1.1.1. Fundamental interactions and universal theories

Over the years, experiments have been performed or proposed in the fields of (1) fundamental interactions and theories such as the search for new long-range fundamental interactions and quantum effects, time dependence of fundamental constants, classical tests of special and general relativity, observation of gravitational waves, search for antimatter and extreme high energy matter, entanglement and de-coherence of quantum states over long distances and times; on (2) self-organisation of matter, such as macroscopic quantum condensates in extremely unperturbed conditions, statistical physics and phase transitions, cluster formation, crystallisation, fluid flows, flow patterns, nucleation, coagulation; and on (3) complex (chaotic and non-linear multi-process) systems.

One of the outstanding questions in our understanding of nature is that two fundamental theories, namely quantum mechanics and general relativity – demonstrated by an enormous wealth of experiments – appear to be in contradiction. All theories trying to solve this paradox call new interactions into play. These interactions, weak and long range, would be superimposed on gravity, mimicking violations of Galileo’s principle of universality of free-fall, also known as the equivalence principle. The search for these forces asks for a large mass source, for example the Earth, very pure free-fall conditions (purely gravitational orbit) and a very quiet environment. Space appears to be the obligatory way to go. Indeed all experiments proposed and studied in some depth, are based on comparing the rate of fall of two bodies, nominally at the same location, due to the interaction with the Earth. In orbit, a difference in the rate of fall will result in a tiny relative acceleration of two orbiting bodies that could be measured with a sensitive differential accelerometer. A similar concept that uses cold atoms instead of macroscopic bodies has also been implemented on the ground and proposed for a flight implementation.

A series of questions about the space-time validity of elementary interactions is tested via the time dependence of fundamental constants, something that can be done only with extremely precise clocks. Free-falling, high-precision atom clocks and hydrogen masers are the key instruments for these experiments. The approved experiment ACES will substantially advance the measurement precision of the time dependence of the fine structure constant, the key parameter of quantum electrodynamics, by comparing the pace of its cold atom clock PHARAO to that of the hydrogen maser.

For bosonic and fermionic quantum matter, gravitational and inertial fields play important roles in several respects. These fields couple adiabatically to quantum states, modulating their properties. This makes the gravitational fields the ultimate disturbance for these systems but also makes the same systems ideal detectors of those fields. This is the reason why in recent years many proposals have been made to test matter-wave interferometry in space and to use the interferometers as detectors of frame dragging and other gravitational effects predicted by Einstein’s Theory of General Relativity. One of these proposals has been studied at system level by ESA as the Hyper mission, an orbiting matter-wave interferometer aimed at mapping the frame-dragging field of the Earth. Second, the Earth gravity forces experiment with cold atoms in general and Bose Einstein condensates in particular, to use levitation and confinement devices. The disturbance due to these devices prevents the condensate from reaching the ultimate low temperatures and an increase in the size of the system. In space, because of the possibility of long-term free-fall, one should be able to reach femto-Kelvin temperatures and open up a regime of new physics not obtainable on Earth. In this very low temperature regime, thermal noise is effectively suppressed, so that one can fully investigate the intrinsic limitations to quantum coherence in these macroscopic systems.

Over the past few years, an impressive series of experiments has been performed in ground-based laboratories on quantum entanglement. Quantum theory does not contain any prediction on the space-time limitation of these non-local correlation effects. Space is the only place where these experiments, all

currently based on photon states, can investigate large distances. On Earth, the fundamental limitation at ≈ 100 km due to the surface curvature, absorption losses in the atmosphere and losses in optical fibre systems is being rapidly approached.

3.1.1.2. Complex plasmas: a new state of soft matter

The need for research in space is obvious in this research field. Since one of the important points of this new state of matter is the (effective) absence of a damping background medium, support against gravity becomes a key issue. In the laboratory this support against gravity can be achieved using electrostatic fields, magnetic gradients and/or thermophoresis. However, for experiments under “low stress” conditions it is essential to use microgravity. This is a rapidly evolving field: 10 years after its beginnings (Thomas et al 1994) the field of complex plasmas has developed a high activity level similar to that of soft matter physics. It was found that since 1994 over 100 research groups have taken up this field. The field of complex plasmas has been fortunate inasmuch as it already has a working “laboratory” (PKE-Nefedov) on the ISS since 2001. Many discoveries have already been made, including the physics of discharging of plasmas and a new charge-induced runaway coagulation (gelation) transition that exceeds the well-known geometric rate by five orders of magnitude.

3.1.1.3. Condensed matter – universality and scaling

Critical phenomena (phase transitions) appearing through manipulation of parameters show universality and a certain scaling behaviour. The universal, scaled behaviour depends only on the space dimensionality D (generally 3, but it can be 2 for surface phenomena) and the dimensionality N of the order parameter (the parameter which breaks its symmetry at the transition). The couple (N, D) defines universality classes. The case $N=1, D=3$ corresponds to the gas-liquid critical point, where outstanding results have been obtained thanks to the space conditions of weightlessness. The class $N=2, D=3$ corresponds to the superfluid transition. The critical temperature between the normal and the superfluid state of a system depends on the pressure. However, when we approach the critical temperature other thermodynamic quantities such as the specific heat, the magnetisation, or the density, behave universally, independently of the pressure. This means that near the critical temperature certain quantities describing

the many-particle system depend on the temperature alone. In these equations there is no reference to the actual system used. Therefore all systems must behave in the same way. This is a very surprising prediction.

Superfluid Helium ^4He is best suited to an experimental study of these predictions of statistical physics, and renormalisation group theory. Many experiments have been carried out using superfluid Helium ^4He on Earth. However, gravity induces inhomogeneities in the system which greatly limits the attainable accuracy of these terrestrial results.

3.1.1.4. Complex systems – atmospheric and cosmic particles

The most important complex system for humanity is our environment. There are many detailed interacting processes that play a role, in a complex and often non-linear function, in determining climate, ocean, land and atmosphere evolution. The influences extend from outside our planet – space – to internal ones produced by humankind itself. By simulating primitive and small solar system bodies – a major part in the ICAPS programme – fundamental properties of these objects will be known by the time of Rosetta’s encounter of with comet 67P/Churyumov-Gerasimenko in 2014.

3.1.2. Physics of fluids and interfaces

3.1.2.1. Fluids with imposed, external body forces

On Earth the behaviour of all fluids is strongly affected by gravity. The effects of external fields (electric, magnetic, driven vibrations, thermal gradients) may be difficult to distinguish in the presence of strong gravitational effects. A low gravity environment provides a unique opportunity to remove the strong limitation that this places on terrestrial experiments, whether aimed at fundamental or applied science.

3.1.2.2. Interface with a solid

Under terrestrial conditions, the capillary length of an air-water interface at room temperature is about 3mm, hence capillary effects always dominate at small scales. There is a noticeable exception at the gas-liquid critical point, where the interfacial tension vanishes. At low gravity, however, the length scales at which capillary effects become important are much larger. The weightless world is thus a rescaled micro sized world. Management of fluids becomes markedly different in orbit, with a strong influence

of wetting conditions and contact angles. Some devices that cannot work on Earth can thus be used as heat pipes with capillary flows.

3.1.2.3. Foams, films and emulsions

Foams and emulsions have properties largely governed by the surface tension associated with the interface between the two phases, but gravity intervenes to cause drainage and separation in most cases. A weightless environment can greatly extend the range of realisable systems.

3.1.2.4. Chemistry and combustion

Combustion is normally accompanied by very large density changes and consequent buoyancy forces that induce natural convection flows. It is therefore radically different in space, where mass transport is mainly driven by diffusion (How will a fire spread in a satellite or a space station?).

Soot and particle formation is also an important topic in microgravity relating to droplet and spray combustion. Because of the absence of buoyancy, microgravity experiments offer the possibility of simple experimental conditions for a more systematic model validation.

3.1.2.5. Supercritical phenomena

Because of these anomalies of the thermodynamic parameters of near-critical fluids in the vicinity of the critical point, they are also very sensitive to gravity. On Earth, buoyancy-driven flows are impossible to avoid, and they obstruct our efforts to understand other basic transport mechanisms. The very large compressibility of the near-critical fluid entails significant gravity-induced density gradients and sedimentation. The microgravity environment of an orbiting platform is ideal for the study of such systems; in particular, it has permitted the discovery of the Piston Effect, a very efficient way to thermalise such compressible fluids, and further discoveries may be anticipated.

3.1.2.6. Granular materials

The description of granular media in terms of continuum mechanics or statistical mechanics still remains an open question and seems to depend strongly on the flow regimes involved. An “effective” temperature can be given to the granular matter by applying mechanical vibrations or alternating accelerations. The possible states that such a “dissipative” matter can assume are mostly unknown and pose many questions. This is particularly interesting as the accretion of dust in the cosmos should obey the same laws.

3.1.3. Materials physics

Europe now has a strong and leading role in the field of materials science and engineering in general and, in particular, constructing complex and multifunctional space equipment, scientific analysis of materials processing in space and new materials for space. Today materials physics is closely related to fluid physics and to some extent to fundamental physics and these days can be considered as nano-engineering, i.e. designing new materials from the nanoscale level up.

Within Europe the production and fabrication of alloys together with the casting and foundry industry in general, generate a considerable amount of wealth. As such, this area of R&D constitutes a major backbone of European industry. The continuation of wealth generation in Europe by these industries relies on the improvement of its competitiveness with Japan, the USA and others in the design and production of materials; for example in aerospace, automotive, biomedical, energy conversion and microelectronics.

The specific environment of microgravity that can be achieved over long periods on board the International Space Station has repeatedly proved to be of value in providing experimenters with a unique complementary way to get rid of the complex distorting effects of fluid flow driven by buoyancy in liquid and gas phases. In this way the unambiguous benchmark data needed to discriminate sound three-dimensional models within the diversity that is proposed for solidification and casting processes can be obtained. Therefore accurate input data are needed concerning the stable liquid and at different levels of liquid undercooling for a full and accurate analysis. Here, a fundamental understanding of fluid flow and heat flow, which are controlled by the thermophysical properties of the melt, is a key issue, and it is also necessary for the active control of industrial processes.

Based on recent experience with space shuttle and parabolic flight experiments, electromagnetic levitation including sophisticated analysis tools has been developed and established as a versatile and reliable technique in studying highly reactive metallic melts. This technique offers several advantages over alternative levitation methods because of the direct coupling of the electromagnetic field with the sample.

On the basis of newly developed analysis and measurements techniques for relevant thermodynamical properties (fluids for advanced processes; new materials, products and processes), a scientific

programme has been established within ESA's MAP activity, relying on the following topics:

- crystal nucleation and growth transients
- columnar/equiaxed growth
- multiphase growth; multicomponent alloys
- non-equilibrium undercooled liquid processing and glass formation
- metallic foams
- magnetic fluids
- protein crystallisation
- growth of non-metals

The ESA-led Intermetallic Materials Processing in Relation to Earth and Space Solidification (IMPRESS) project has recently been selected by the European Commission as a flagship project in materials science and applications. The project comprises a large multidisciplinary consortium of 43 European research groups and companies and has the potential to make Europe a world-leader over the coming years in this strategically important area of materials physics. The key scientific objective of the project is to develop new knowledge about the relationship between processing, structure and properties of intermetallic alloys. The ISS, as well as other microgravity platforms, will be used extensively to perform benchmark experiments on these advanced intermetallic alloys. The unique data from these microgravity experiments will make a vital contribution to the project.

3.2. Life sciences

3.2.1. Human and animal physiology

3.2.1.1. Cardiopulmonary physiology

The classic hypothesis as to how the human cardiopulmonary system and the renal control of fluid and electrolyte balance adapt to weightlessness has been challenged by data from space. Originally it was hypothesised that weightlessness would induce central blood volume expansion that would lead to an augmented renal output of electrolytes and fluid. That central blood volume is increased by weightlessness was confirmed in the mid-1990s, because the heart is distended. The mechanisms for this, however, are surprising, because the increase in central blood volume is not only accomplished by the abolition of hydrostatic pressure gradients in the circulation but also by a decrease in interpleural pressure. Even though the heart and central vessels are distended in space, an augmented renal output of fluid and electrolytes has not been documented (Drummer et al. 2001; Norsk et al. 2000). This has led to the hypothesis that sodium might be stored in interstitial tissues, which is a new concept in human physiology (Heer et al. 2000) and which has led to development of new experimental models on the ground. If this new hypothesis is confirmed, it will have implications for understanding why some people develop hypertension.

Data from space have also led to the discovery that gravity affects the cardiovascular system in a front to back direction and vice versa in horizontal humans. Rohdin et al. (2003) observed that humans in the prone position during hypergravity oxygenated the blood more efficiently than humans in the supine position. This discovery will have important implications as to how to position patients with cardiovascular disease.

3.2.1.2. Bone

In space, despite physical training, bone loss is an adaptive process that can become pathological after recovery on Earth. Striking interindividual variations in bone responses seem to suggest a need for adequate crew preselection. Targeted treatment or prevention strategies would be useful, not only for space purposes, but also for the increasing number of osteoporotic patients on Earth (Vico et al. 2000).

3.2.1.3. Neuroscience

Prolonged microgravity during orbital flight is a unique way of modifying the otolith inputs and to

determine the extent of their contribution to the vertical vestibulo-ocular reflex (VOR) and optokinetic nystagmus (OKN). Clement (2003) has recently reviewed data collected on 10 astronauts during several space missions and reported on changes in the up-down asymmetry. Both the OKN elicited by vertical visual stimulation and the active VOR elicited by voluntary pitch head movements show an asymmetry before flight, with upward slow phase velocity higher than downward slow phase velocity. Early in-flight, this asymmetry is inverted and a symmetry of both responses is later observed. An upward shift in the vertical mean eye position in both OKN and VOR suggests that these effects may be related to otolith-dependent changes in eye position which, in themselves, affect slow phase eye velocity.

3.2.2. Biology

The following paragraphs give some examples for the development and achievements in the different biology fields which are directly related to space experiments. The list is by no means exhaustive.

3.2.2.1. Molecular and cell biology

Experiments in microgravity so far reveal that cellular systems sense the absence of gravity and that many functions in humans, such as bone development, heart function and immunocompetence are altered. Although the end result of these microgravity effects is not yet known it has been suggested that one reason might be the direct effect of gravity on the cellular level, and one hypothesis proposes an increase of programmed cell death (apoptosis) in microgravity. Recent studies in microgravity and hypergravity concentrated on the cytoskeleton and signal transduction chains, as they control fundamental cellular functions, such as maintenance of cell architecture, cell motility, cell division, regulation of enzymes, ion channels and gene expression. Going beyond pure description of the phenomena to an understanding of the microgravity-induced alterations on the molecular and cellular level increases our knowledge in basic science. This will have important implications for human health; for example, depression of the immune system or the induction of cancer which may become serious health issues on long-term space flights.

3.2.2.2. Plant biology

The flowering plant *Arabidopsis thaliana* is a unique model that is used to elucidate the molecular mechanisms of gravity perception and transduction in higher plants. This model system allows the identification of the genes controlling gravity responses and

the determination of their function. The many genetic and molecular tools for analysis of molecular processes make this very small organism ideal for research on the ground and in space.

Over the last couple of years, major advances have been made in understanding gravity signalling in *Arabidopsis thaliana*. Finally, after many decades, an hypothesis for gravitropism of the root was verified, the molecular basis of which has been indentified. Some of the major players in gravity signalling were identified and information obtained on gene networks affected by gravity on Earth and in space using gene chips covering the full genome of this plant. These data now provide the basis for detailed cellular analyses of gravisensory/mechanosensory processes.

3.2.2.3. Developmental biology

Current developmental biology faces a paradox: while cells are clearly reacting to the absence of gravity by modifying their cytoskeleton and signal transduction pathways, overall development seems to be ultimately unaffected. A better understanding of the developmental regulation mechanisms could reconcile these apparently contradictory results. In this respect it is important to proceed with long-term experiments (the ISS may allow this) that had been impossible in the past. It could be that there are still effects that cannot be perceived in short-term experiments but become apparent in long-term experiments. Thus it is necessary to better understand (1) how the phenotype is actually produced from the instructions stored in the genotype, and (2) the nature of the actual mechanisms influencing the extent to which physical and other external forces and processes contribute to the shaping of particular organisms. These data are critical for the evaluation of the possible outcome of extraterrestrial colonisation attempts. They are also critical for our scientific capability of giving answers to most problems in our ground base, the Earth.

Periods of life, revealing an extremely high sensitivity to altered environmental conditions, characterise the development of sensory, neuronal and behavioural functions. They are called “critical periods”. Space experiments involving fish and amphibians reveal critical periods for the development of the vestibular system. During space flights (Shuttle; Soyuz/ISS), a typical response called the vestibulo-ocular reflex, which is induced by stimulation of the gravity sense organs (see Figure 6.3), was significantly modified in an age-related manner by gravity deprivation. Most prominent was the observation that the vestibular system became more sensitive during

the space flights, a feature which is in line with observations on gravity perception in astronauts.

3.2.3. Exobiology

The recommendations of the Bischenberg workshop identified the following three topics as research goals and questions to be addressed within the field of exobiology, the subjects of which are interlinked: (1) exobiology packages for exploration science missions with the targets Mars, Europa, comets, other solar system bodies and extrasolar planets; (2) chemistry of the origin of life; and (3) biological evolution of life. The following steps have been taken by ESA in due consideration of these recommendations.

3.2.3.1. Exobiology packages for exploration science missions

Within the ESA programmes several space missions are in progress that have key objectives concerning the nature of extraterrestrial organic chemistry and the search for traces of past or present life on other bodies of the solar system. These include Mars Express (to Mars), Cassini-Huygens (to Saturn and Titan), and Rosetta (to the comet Churyumov-Gerasimenko). Concerning the search for life on Mars, orbiters, such as Mars Express are providing data on the geology (paleolakes, volcanism, hydrothermal vents, aqueous precipitates), climate (hydrosphere, duration of phases which allow liquid water) and radiation environment required for assessing its past and present habitability. The search for possible biological oases is connected with the detection of areas where liquid water still exists. In this connection, the finding of methane in the atmosphere of Mars by Mars Express is intriguing.

ESA has initiated an exobiology approach to the exploration of the solar system by coordinating the study "Exobiology in the solar system and the search for life on Mars" (ESA 1999) which resulted in the recommendation of a suitable lander/rover package that includes subsurface drilling capabilities to search for signatures of life on Mars. This instrument package is the core of the proposed Pasteur payload for the rover of the ExoMars mission planned for 2011. After a call for idea proposals by ESA, 22 out of 50 proposals were selected and the selected teams are currently optimising the payload to serve the three objectives (search for past life, search for present life, and hazards to humans). This mission will pave the way for an international Mars Sample Return mission in 2016 in which Europe would provide the sample collecting rover and the drill capabilities. The critical health issues in connection with human missions

to Mars have been assessed in the HUMEX study by ESA (ESA 2003).

In order to learn more about the survivability and adaptive strategies of candidate microorganisms under Martian conditions, which is considered a prerequisite for search-for-life studies, the Topical Team, Responses of Organisms to Martian Environment (ROME) was set-up by ESA in 2003 and a laboratory programme on complex organic chemistry in a Mars simulation chamber has started. Concerning planetary surface missions, ESA has established a planetary protection working group, is organising planetary protection courses, and has started an active planetary protection programme.

3.2.3.2. Chemistry of the origin of life

For exobiology studies in Earth orbit, ESA has developed two facilities to expose organic and biological specimens to the conditions of outer space and to study their responses after retrieval. These are (1) the BIOPAN facility on board the Russian satellite Foton which stays for about two weeks in Earth orbit, and (2) the EXPOSE facility to be mounted on an external platform of the International Space Station. BIOPAN will resume its flights in 2005 and EXPOSE is scheduled for launch in 2005 and again in 2007-08 and will stay in space for more than a year. Exposing samples to the specific environment of outer space allows research directed towards understanding prebiotic chemical evolution processes such as interstellar organic chemistry, photochemical processing in space, emergence of prebiotic molecules in space, and the delivery of organics to a planet.

3.2.3.3. Biological evolution of life

The facilities BIOPAN and EXPOSE also provide opportunities for studying the limits of life in extreme environments. By using optical filters, the biological effects of selected spectral regions of solar UV radiation can be studied. Questions to be tackled include the impact of UV radiation climate on Earth's earliest biosphere, the role of an ozone layer in the screening of biologically harmful UV radiation, the habitability of other planets (for example Mars), and the chances and limits of interplanetary transfer of life, and the protection of microorganisms by meteorites. The results obtained from such space experiments have supported the hypothesis of "lithopanspermia", namely, that resistant microorganisms might withstand the severe strain in outer space thereby surviving a hypothetical journey from one planet to another protected within meteorites. Currently, the experiment requirements and test parameters are being veri-

fied during a set of experiment verification tests (EVTs).

3.2.3.4. Use of ground-based facilities

The participants of the Bischenberg workshop further recommended that ESA should support ground-based work in mission preparation, laboratory testing, terrestrial analogues etc. A strong ground-support programme would substantially support the realistic planning of future space experiments as well as search-for-life experiments. With the ground-based programmes SSIOMUX (Space Simulation for Investigating Organics, Evolution and EXobiology) and Complex Organics on Mars, ESA has started to support ground-based studies in connection with exobiological research. Another interesting approach is the ESA Topical Team, Boundary of the Biosphere which has the aim of designing experiments for exploring the vertical profile and the upper boundary of the biosphere by use of rockets or balloons, sterile sampling devices, and modern molecular biology analysis. Concerning Bioregenerative Life Support Studies (BLSS), the ESA-funded REGLISSE study defined European facilities suitable for preparative ground-based studies ([http://www.estec.esa.nl/ecls/melissa/ attachments/REGLISSE](http://www.estec.esa.nl/ecls/melissa/attachments/REGLISSE))

3.2.3.5. Outreach and education

Following recommendations from the Bischenberg meeting to establish a structure and budget for effective outreach and education activities, ESA has established the Virtual Institute of Exobiology at ESA/ESTEC (<http://www.spaceflight.esa.int/exobio>) thereby providing a platform for communication, training and education in the field of exobiology. This virtual institute also hosts the web page of the European Astrobiology Network Association (EANA) a network that currently links scientists active in exobiology from 17 European nations.

3.2.3.6. Internal structure of ESA

To maintain and manifest European competitiveness in this rapidly emerging field of exobiology, it was recommended that ESA strengthen its role as a coordinator and supporter of international collaboration in the field of exobiology. It was also felt that, as the programme is science driven, the ESA management structure needed to be changed and a scientific advisory structure for an interdisciplinary activity was required. Several steps have been taken by ESA in this direction, such as the preparatory phase of the Aurora programme with its Exploration Programme Advisory Committee.

Chapter 4: Scientific recommendations

The following specific recommendations are made in response to the needs of the disciplines and based on the clear research in space requirements and the scientific quality of the research proposal:

4.1. Physical sciences

4.1.1. Fundamental physics

- Build the IMPACT facility, and
 - support predevelopment of ICAPS and IMPF hardware for the IMPACT facility
 - support parabolic flight campaigns for PK and ICAPS precursors
 - build the IMPF precursor experiment PK4
 - support use of PK3+ in the interim science programme.
- Finance a Phase A study for a Bose-Einstein condensate experiment insert in the IMPACT facility.
- Finance a Phase A study for investigating an IMPACT insert for studying universality concepts near the critical point in liquid complex plasmas (kinetic measurements).
- Set up a virtual laboratory network for IMPACT-related research (pilot programme for ISS generally.)
- In long-range quantum communication and entanglement experiments, the substantial leap in the scale of these experiments which would be allowed by a space-borne implementation, is to be actively pursued.
- For precision measurements requiring more demanding performance of cancellation of gravitational field, actively explore:
 - the possibility of developing a multipurpose drag-free platform to perform these experiments;
 - the intermediate implementation of some of these experiments on existing facilities, as an enabling step toward the final experiment on such a drag-free platform.

4.1.2. Materials and fluid sciences

- It was felt that the current strategy of the ELIPS research plan should be continued, i.e. with the following principles:
 - it should be science *and* application driven
 - the underlying principle should remain best science driven by academia

- the application aspects should be driven by industry
- European coherence (including industry) should be sought
- education and outreach should be a main element of the programme.
- The number of flights must be increased, and existing programmes continued, including the facilities for Columbus. All activities of materials/liquid phase physics depend critically on the availability of advanced flight hardware for the International Space Station; for example,:
 - electromagnetic levitation (EML) (international)
 - glove box inserts (international)
 - advanced crystal growth facility (international)
 - metallic liquids in magnetic fields (French activity)
 - new X-ray in situ diagnostics (international)
- A specific goal, nano-engineering, has been identified, with a focus on material design from the atomic scale, up.
- Concerning the cornerstones identified at the Bischoff meeting, no basic change was required but the programme goals should be made more ambitious and clearer.
- Beyond these cornerstones, one should study (1) thermophysical properties to analyse casting processes and develop a theory of high-temperature melts, and (2) material design from fluids.

4.1.2.1. Unexplored research areas where breakthroughs can be expected

Thermophysical property measurements under microgravity are the essential way to obtain precise data against which theories can be tested. The measurement of these properties on Earth is most often so inaccurate that in a grossly simplified way, every theory is able to make predictions to which some measurements will fit. Therefore, microgravity is essential in understanding the nature of molten metals and alloys. Experiments to be performed are:

- 1g EML: flow velocity ca. 32 cm/s ($Re \sim 2800$) dominated by large magnetic fields;

- 1g EML: flow velocity ca. 4.4 cm/s ($Re \sim 110$) dominated by Marangoni convection due to laser heating;
- micro-g EML: wide range of fluid flow conditions from 0.1 cm/s to 18 cm/s due to quasistatic acceleration levels and controllable magnetic fields; heat flow determined by radiation due to containerless processing in UHV;
- This microgravity research must be accompanied by ground based research looking into structural arrangement by, for example, synchrotron radiation, neutron scattering, EXAFS etc.

4.1.2.2. Nano-engineering from fluids

This field connects with fluid physics and fundamental physics, related to the topics of solidification, crystal growth (metallic, non-metallic, transparent materials), materials production from the vapour phase, protein crystallisation, porous composites/metallic foams, colloid crystals (plasma crystals, agglomeration of nanocrystals), sol-gel processes.

There is an unknown effect of fluid flow (heat and mass transport) on the dynamic, non-linear response of the crystallising system, microstructure evolution etc. So far only semi-empirical modelling efforts are undertaken. Microgravity research on solidification is the only method to yield breakthroughs, since:

- well-defined boundary conditions for mass and heat transport are set by the absence of gravity; and
- well-controlled conditions of artificial fluid flow can be induced there, for instance in the MSL using rotating magnetic fields, not being disturbed by any kind of gravity-driven convection which is uncontrollable and complicated to describe even numerically in the self-organisation structure of a mushy zone.

Further efforts must be made in:

- understanding pattern formation and self-organisation in the non-linear dynamics of solidification and crystal growth of metallic melts and in colloids (magnetic fluids) and sol-gel processes;
- quantitative, predictive physical models of the effect of fluid flow on microstructure evolution; and
- modelling of technical processes from the liquid to the solid state, from the nano- to the macroscale.

Furthermore, this area of research is of a very interdisciplinary nature and clearly implies close cooperation with the fluid physics community and to some extent to fundamental physics. Two areas of interdisciplinary research have been further defined for the

future and might be activated by the formation of two new topical teams:

- *Nucleation*: bridging the activities in metallic materials to more complex systems, such as proteins, semiconductors, complex macromolecules.
- *Self-organisation*: This feature is encountered in systems far from the thermodynamic equilibrium. During this process spontaneous structure formation can occur, driven by external or internal forces. Examples are dendrite formation where the instability of the solid/liquid interface results from the amplification of fluctuations at the growth front, fluctuations in the protein concentration before nucleation, in plasmas etc.

In fluid physics, the cornerstone Physics of Fluids identified in the Bischenberg meeting should be replaced by *Physics of fluids and interfaces*.

Several new facilities or instruments should be developed to fit the identified programme cornerstones; these encompass:

- a facility for supercritical chemistry
- a facility supporting investigations in vibrational physics
- advanced diagnostics to support combustion research in ground based free-fall facilities (PF and drop-tower).

Overall, it is felt that the coordination between ESA's and national programmes should be improved by extending to ESA the ability to support ground-based research (for example, by opening the Technology Research Programme to academia). In this context, the importance of supporting ground-based activities is identified in the EU's White Paper (COM/2003/673). From that perspective, IMPRESS opens the way to a new form of support by the EU.

Europe should develop its own platforms and transportation systems to take into account the impact of the US situation (retirement of STS, foreseen end of ISS utilisation phase, new exploration policy).

Concerning the exploration programme and the issue of a human presence in space, fluid management (propulsion, storage, heat transport, combustion etc. in space is a key problem of space exploration. Coordination with space technology developers must be implemented in the field of propulsion, thermal exchanges, cryofluids, fluid storage, etc.

4.1.3. Vision for the future ELIPS programme

Independent research efforts must continue to be supported in Europe, but in compliance with NASA, and its vision for space exploration, advocated in February 2004. The ISS is an instrument for the exploration of space, where critical experiments must be carried out (heat transfer, propulsion, advanced materials, fire safety).

Europe's materials research supporting programme elements are:

- radiation protection programme
- in situ use programme
- in situ fabrication and repair programme
- in space propulsion materials programme.

Human health and performance issues, radiation protection issues (radiation exposure and mission requirements, radiation measurements technologies, shielding solutions etc are paramount. Hence, studies concerning the following topics must be carried out:

- accelerator measurements of new materials
 - multifunctional shielding materials for spacecraft and spacesuits
 - regolith-based shielding composites
 - nanomaterials for radiation environment protection
 - magnetic materials
 - bonding technologies (brazing, welding, self-healing)
- etc.

Advanced space programme technologies must be developed, such as:

- advanced materials and structural concepts
- advanced ablative and reusable thermal protection system materials
- fabrics with high thermal conductivity
- aerogel thermal insulation
- high strength to weight materials
- high temperature composite materials
- self-healing seals
- wire insulation
- multifunctional materials with integrated electronics, sensors and actuators
- power, propulsion and chemical systems programme.

4.2. Life sciences

4.2.1. General scientific recommendations

General scientific recommendations common to the life sciences reflect the following opinions, most of them related to assuring scientific excellence.

- The scientific programme of ESA should be user-driven.
- ESA should encourage supporting research by the use of ground-based facilities and basic but relevant ground research.
- ESA should more strongly emphasise that space experiments must be embedded in strong basic science in the applying laboratory.
- ESA should provide the means, on the basis of the following recommendations, to evaluate research in space in such a way as to ensure that the results appear in high-ranked journals.
- ESA should provide more flight opportunities so that excellent European research in space is not hindered by reliance on non-European flight opportunities.
- ESA should ensure that equipment on the ISS is maintained and updated and that conditions in space are well controlled and monitored.
- ESA should facilitate the development of necessary hardware according to the needs of selected proposals.
- ESA should extend and continue its activities in outreach and education.
- ESA should foster interdisciplinary cooperation with other disciplines within the ELIPS programme and other relevant programmes in preparation for human exploratory missions.

The specific scientific recommendations for each sub-discipline are as follows:

4.2.2. Specific scientific recommendations

4.2.2.1. Human and animal physiology

• *Scientific excellence*

- ESA should continuously make sure that scientific excellence is the main criterion for selection of research projects. In order to ensure this, the scientific programme has to remain user driven in the future. It is mandatory that there is more frequent access to space than at present, that the equipment is maintained and updated and that the conditions in space are well controlled and monitored.
- To ensure a high scientific quality, the proposers should not be limited by the question of whether the hardware is available, because the selection of

the proposal for implementation for flight should primarily be based on the scientific rating. If a proposal is deemed to be excellent but cannot readily be implemented for flight, because the equipment is not yet available, ESA should facilitate the development of the necessary hardware. In this way, scientific excellence will not be sacrificed for temporary technical reasons.

- To obtain as high a scientific quality as possible, ESA should make sure that the number of test subjects required by the investigators is obtained, even though the experiments have to be conducted on several space missions. It is more important to conduct a few experiments satisfactorily than to fly many experiments, in which the scientific requirements are not met.

• *Structure of the programme*

It is suggested that the cornerstones from the Bischenberg meeting be restructured so that they will better fit the more applied aspects of the future exploration/manned space programme. The cornerstones therefore consist of a basic physiological part (1), which covers integrative physiology and two more applied parts (2 and 3), which cover other influences of gravity on the body during spaceflight and countermeasures against these influences and those of weightlessness. The suggested cornerstones are therefore:

- *Integrative gravitational physiology:* To explore in an interdisciplinary way systems, which are sensitive to gravity, such as (but not limited to) the: cardiovascular system, pulmonary system, nervous system, fluid-electrolyte homeostasis, skeletal system, muscular system, immune system, etc.
- *Non-gravitational physiology of spaceflight:* Exploring effects of the non-gravitational extreme environments of space such as (but not limited to): nutrition, radiation, isolation, confinement, noise, disruption of circadian rhythms, immobilisation, hypobaric conditions (e.g. EVA), etc.
- *Countermeasures:* Developing physiological, pharmacological, psycho-logical, and mechanical countermeasures against (but not limited to): spatial disorientation (nausea, imbalance), orthostatic intolerance, bone loss and microarchitectural deterioration, muscle atrophy and weakness, cardiac atrophy, radiation, nutrition, etc.

In addition, it is suggested that the three cornerstones be supported with facilities, that give access to microgravity (parabolic flights, ISS, taxi flights), microgravity simulation studies (bed rest, water immersion

etc.), changes in gravity on the ground and in space (centrifugation, short-arm centrifuge etc.), and animal facilities, also on the ground and in space.

• *Encouragements to scientific users*

Scientists are encouraged to:

- be interdisciplinary in their approach.
- explore interindividual differences
- conduct comparisons with clinical (pathophysiological) conditions
- realise the full research potential made possible by the highly selected group of astronauts
- conduct gender comparisons
- perform interspecies comparisons.

• *Comments to recommendations of the Bischenberg meeting:*

- The programme should continue to attract non-space scientists, who can use microgravity as a tool in their research. However, ESA should do more to make the announcements of opportunity (AOs) widely known through advertisements in scientific journals and better outreach through the press. Efforts to arrange workshops and advanced research courses should be promoted.
- ESA should continue to encourage networking among scientists in preparation of the responses to AOs.
- AOs should be issued more frequently than now and at least once every year and more flight opportunities than now should be offered to the scientific community.
- The peer reviewing process at ESA of life science proposals is of satisfactory quality and should be continued.
- ESA should to a higher degree than now conduct evaluation of the scientific results of completed space missions and adjust the programme accordingly.
- It is considered very important that the scientific results of the programme are published in non-space scientific journals and that the space results are distributed to as wide a scientific audience as possible.
- The “pyramids” previously featured in the ELIPS research plan should be discarded and substituted by the suggested structure of the programme described above.
- ESA should continue through the MAPs, for example, to induce spin offs of the results of spaceflight into medical treatments and procedures, development of instruments and equipment etc., and by using the ISS as a test-bed for studying diseases.

- It is mandatory to the scientific success of the programme that the most updated equipment is available and that the conditions in space are as well controlled and monitored as possible.
- It is recommended that a link be established between cornerstones 2 (*Non-gravitational physiology*) and 3 (*Countermeasures*) of this programme and the Exobiology programme for interplanetary manned explorations.

4.2.2.2. Biology

• Recommendation 1

The peer review process for proposals currently established by ESA is very effective. However, ESA should more strongly emphasise that space experiments must be embedded in strong basic science in the applying laboratory.

• Recommendation 2

Publication of results in high-ranked journals is a key requirement. Among other aspects, it may be decisive in attracting other scientists to the field. ESA should provide the means, embedded in the following recommendations and evaluate the research in this respect.

• Recommendation 3

Because of different restrictions incorporated in the general policy of the agency, ESA does not support ground research. However, as mentioned above, strong ground-based research is an indispensable requirement for high-quality space experiments. ESA is therefore advised to initiate programmes to support accompanying ground research as soon as possible. A complementary, additional support of space-related ground research by the EC would be much appreciated. PhD and educational programmes dedicated to the three biological cornerstones should be funded by the EU (Marie-Curie network) on the basis of ESA recommendations and negotiations. Finally, the coordination between ESA and the national space agencies/programmes should be strengthened, in particular in the actions where both partners share responsibilities such as the reviewing and funding of approved projects.

• Recommendation 4

ESA should encourage interdisciplinary and multi-laboratory applications including the high throughput technologies fostering integrative studies from the gene to higher systemic levels. This would allow for the most effective use of the scarce flight opportunities. In this respect a public database with infor-

mation about available biological materials would be helpful. In addition, interdisciplinary approaches are crucial for answering questions important for the understanding of the relationships at different levels between simple and complex systems as well as the impact of radiation on organisms.

• Recommendation 5

There is remarkable expertise in Europe for competitive science in the biological cornerstones. The main weakness derives from the dependency of European scientists upon non-European flight opportunities. With the prospect of short-term limitations in access to the ISS, the biology group strongly advises ESA to continue the current programmes for sounding rockets (TEXUS, MASER and MAXUS), satellites (Foton) and parabolic flights. Any feasible initiative that will reinforce the independence of Europe's flight capability should be given serious attention.

• Recommendation 6

The biology group feels that besides the existing or planned facilities, some new facilities are necessary in the near future. Cell culture facilities, different kinds of bioreactors, standard preservation facilities, a quick and deep-freezing facility in space for the emerging high-throughput technological approaches, advanced microscopy with observation possibilities of flight samples on the ground, NIZEMI (upgrade to fluorescence techniques) and automated facilities to support development, growth and harvesting of model systems are required to accommodate the needs of the growing number of promising new research lines.

In addition, ground-based facilities should be increased (for example, RPMs at each USOC). For a better understanding of the additional (besides microgravity) influence of space radiation on model systems, access to accelerators and strong radiation sources is required.

• Recommendation 7

The biology group considers that the cornerstone system is a valid description of the current status. ESA is asked to modify some of the cornerstones in order to adapt to new developments in the last couple of years.

The group proposes to change the cornerstone Biotechnology to *Molecular and cell biology*. Biotechnology was and is included as a potential application of the findings in all cornerstones (and is implemented in the MAPs). In the context of the

renamed cornerstone, an understanding of the impact of gravity on the cellular and molecular level is intended. Molecular and cell biology aims at the identification of primary targets for gravity. Studies will be performed to analyse gene expression in an altered gravitational environment in relation to cellular phenomena. This includes the improved understanding of the impact of gravity on signal transduction and the specific properties of cellular entities such as the membrane. Furthermore, the role of mechanical forces including those derived from gravity in triggering proliferation, differentiation, apoptotic processes and tissue formation should be clarified.

As potential applications the following items were identified: Molecular and cell biology provides the basis for other disciplines, including developmental biology, physiology, health science (bone and immune system) and biotechnology. Scientific research in this field will give basic information for understanding the impact of long-term space conditions for living subjects. The impact includes, apart from microgravity, specific radiation effects (for example, HZE particles). One important goal is to develop new techniques and to identify pharmacological substances for tissue regeneration etc.

The cornerstone Plant Physiology should be renamed *Plant biology* indicating the importance of cellular and molecular approaches. This cornerstone covers the analysis of the impact of gravity on plant systems, namely the study of mechanosensory elements involved in graviorientation and gravishaping. The aim of the cornerstone is to identify molecular and cellular elements of mechanosensory mechanisms and gravity-related signalling pathways, as well as the determination of how gravity shapes plant morphology. Potential applications include the improvement of plant breeding, propagation and production for use in space and on Earth. Another application is the further development and improvement of biological life support systems. Plant biology will provide the basis for biotechnological applications (for example, farming for production of essential molecules such as vitamins, amino and fatty acids in long-term space flights, as well as antiviral and anti-reactive-oxygen-species substances (for example, to prevent radiation damage).

The cornerstone Cell and Developmental Biology should be renamed *Developmental biology*. The understanding of the impact of gravity on developmental processes is the main scientific target in this research area. The aim is to analyse the mechanisms of how gravity affects animal and plant development,

ageing, pattern formation, morphogenesis, tissue interactions and how these processes are regulated. In addition, gravity-sensitive phases in multicellular organisms will be identified.

• **Recommendation 8**

Recently, in space biology a transition from the “simple” effect detection to a molecular analysis and description of the influence of gravity and radiation on cells and organisms has taken place. ESA should encourage new experiments, whenever possible, to be performed with established model organisms in order to enhance the acquisition of molecular information. However, new scientific developments might require new model systems.

• **Recommendation 9**

The group recommends the establishment of a topical team for addressing questions relating to how gravity drives evolution (from simple to complex systems); this topic also has strong relations to basic physical science and exobiology (namely the origin and evolution of life).

• **Recommendation 10**

The current attempts regarding the communication of scientific results by ESA (Erasmus Experiment Archive, EEA) are highly appreciated. ESA is advised to require that all scientists involved in space experiments supply all relevant literature references and hardware description materials. This initiative should also incorporate information on the Russian-driven experiments and results.

• **Recommendation 11**

At the Bishenberg meeting, outreaches as well as education were identified as major tasks for the mid-term future of the programme. Outreach in respect of public relations could be enhanced by better pre- and post-flight public communication coverage by ESA. ESA's public recognition must be increased by ESA's own efforts and also by efforts of the involved laboratories. On the other hand, these efforts should not interfere with the performance of the research activities in space.

4.2.2.3. Exobiology

• **Recommendation 1**

ESA should continue its efforts in exploring Mars which is considered the prime candidate for the detection of signatures of life beyond the Earth. ExoMars with its Pasteur payload and the three research goals (search for past life, search for pres-

ent life, and hazards to humans) would ideally be the next step in this direction.

• **Recommendation 2**

Exploring Europa's sub-ice ocean and its potential for habitability will be another important highlight in exobiology. As a preparatory step, ESA should initiate a study on the habitability of Europa's sub-ice oceans, its potential biota and a suitable mission scenario.

• **Recommendation 3**

The abovementioned activities to search for signatures of life on other planets and bodies in our solar system must adhere to strict planetary protection rules. Therefore ESA should foster its planetary protection activities. The technological measures to prevent cross-contamination of planets and other bodies during space exploration need to be further developed as we gain more and more knowledge about putative life on other planets of our solar system.

• **Recommendation 4**

ESA should further foster exobiological research in Earth orbit by providing exposure facilities on the ISS and on autonomous free-flying satellites. Additions or changes to future facilities should include the provision of a sun-pointing device and temperature control that maintains sub-zero temperature during sun exposure.

• **Recommendation 5**

Concerning the preparation of human exploratory missions, ESA should foster interdisciplinary cooperation within the ELIPS programme and with its other relevant programmes. Contributions by the astrobiology and planetary exploration discipline include the development of life support systems including bioregenerative approaches; the detection, control and prevention of microbial contamination, and investigations of the radiation field in space and its biological effects. The studies require preparatory robotic space missions, use of the ISS, as well as supportive ground-based studies.

• **Recommendation 6**

ESA should continue supporting research using ground-based facilities to gain information required for designing appropriate search-for-life experiments on Mars and Europa, and to elucidate potentially important pathways of prebiotic synthesis.

• **Recommendation 7**

ESA should consider supporting field studies in regions which are suitable terrestrial analogues of extraterrestrial habitats. This will allow the testing and validation of sensitive detection devices for signs of past and present life in preparation for life detection experiments on Mars and Europa and to train technicians and scientists involved in future planetary missions.

• **Recommendation 8**

ESA should continue and extend its activities in outreach and education. In this context, the establishment of training opportunities in exobiology for PhD students and postdoctoral co-workers is recommended. This would contribute to building a space oriented community, especially in the emerging field of exobiology which so far lacks training programmes at European universities. ESA should extend the publication of its research activities to a broad scientific community in order to be as competitive as possible on a European scale (for example via ESF Member Organisations, learned societies and/or the European Federation of Biotechnology (EFB)). ESA should improve its publicity regarding European activities in research in space; for example, by producing more attractive websites, more press releases and television documentaries.

Chapter 5: Physical sciences

5.1. Fundamental physics

5.1.1. Introduction: the meaning of fundamental physics

Fundamental physics has different definitions in different scientific realms. The discipline indicates here a set of critical unanswered questions about the fundamental laws of nature that need to and can in principle be addressed by space experiments. These questions reach from the fundamental nature of space and time to that of elementary interactions and symmetries, from quantum phenomena and measurements within the macroscopic world, to complexity, self-organisation, and non-linear phenomena.

For instance, over the years, experiments have been performed or proposed in the fields of *fundamental interactions and theories* such as:

- search for new long-range fundamental interactions and quantum effects
- time dependence of fundamental constants
- classical tests of special and general relativity
- observation of gravitational waves
- search for antimatter and extreme high energy matter
- entanglement and de-coherence of quantum states over long distances and times;

and on *self-organisation of matter* such as:

- macroscopic quantum condensates in extremely unperturbed conditions
- statistical physics and phase transitions
- cluster formation, crystallisation
- fluid flows, flow patterns
- nucleation
- coagulation

and finally on *complex systems*; for example

- chaotic systems
- non-linear multiprocess systems.

These set of experiments gives then a limited but practical definition of fundamental physics in space.

The ELIPS programme and research in space play a vital role in our quest for new knowledge and in our desire to look beyond current frontiers of knowledge. Needless to say, advances in basic understanding of the properties of matter, the laws of interaction forces etc. eventually brings economic benefits, even major

ones, when one considers that nearly 40% of our Western economy is based on quantum mechanics and that an application of Einstein's theory of relativity can now be bought, neatly packaged, in navigation devices sold in supermarkets. Similar developments will happen as a result of progress in other areas of fundamental physics research, – they just take their time, of course (figure 5.1).

5.1.2. Special relativity

The Theory of Special Relativity plays a role of central significance in our understanding of nature, as well as being of great practical importance. Special relativity is a theory that has to be incorporated into all other physical theories such as, for example, the theory of gravity: General Relativity. And although we may not be aware of it, special relativity is also absolutely necessary in our everyday lives; such as in the proper functioning of the Global Positioning System (GPS) and also for the forthcoming European Galileo system, for example, which has to take the effects of special relativity into account. In fact, if all special relativistic effects were neglected then positional errors of the order of 10km per day would accumulate – certainly an effect that must be mitigated in circumstances where, for example, an aircraft has to land at a fog-bound airfield.

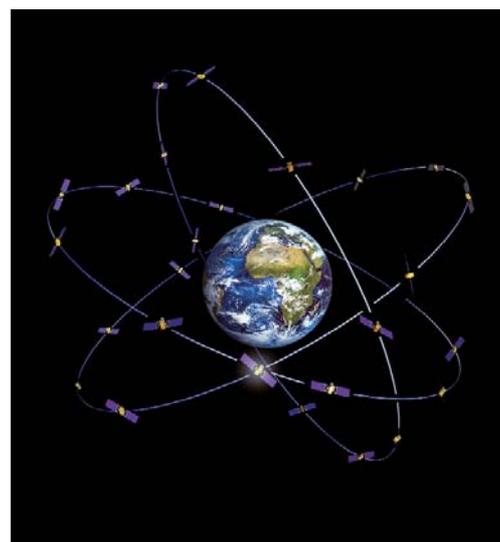


Figure 5.1. The forthcoming Galileo positioning system
Source: ESA – J. Huart

5.1.3. Why fundamental physics in space?

All the experiments mentioned above need space as the laboratory for fundamental reasons. A list of the most relevant reasons follows:

- Very long free-fall under very low gravity conditions; for instance, this is of paramount importance for cold atom physics. Atomic clocks are based on the interrogation of an isolated atomic system. On-orbit conditions allow these types of systems to fall freely for very long times that cannot be achieved on the ground. In addition in 0g, extremely low temperatures can, in theory, be achieved with Bose-Einstein condensates, and also, “complex plasmas” require low gravity conditions for low stress kinetic measurements of critical processes and self-organisation.
- Very low acceleration and self-gravity noise. Gravitational and inertial fields are the ultimate disturbance for many experiments that need to measure

small forces at very low frequency. Equivalence principle experiments, antimatter gravitational properties, matter-wave interferometers are examples of this kind of experiment that needs extreme free-fall conditions that can be achieved only in space.

- Large distances. Many experiments need a scale of distances that can be achieved only in space. Gravitational-wave observatories are a well-established example, but spatial de-coherence of entangled quantum states also now require to go beyond the $\approx 100\text{km}$ scale allowed by the Earth’s curvature.
- Using the Earth as a field source, as in experiments that measure accurate gravitational red-shift from altitude variations along the orbit, or the equivalence principle experiments that look for anomalous coupling of test-bodies orbiting the Earth.
- Being above the atmosphere is necessary for all high-energy detectors aiming at extreme high energy cosmic rays or antimatter or dark matter.

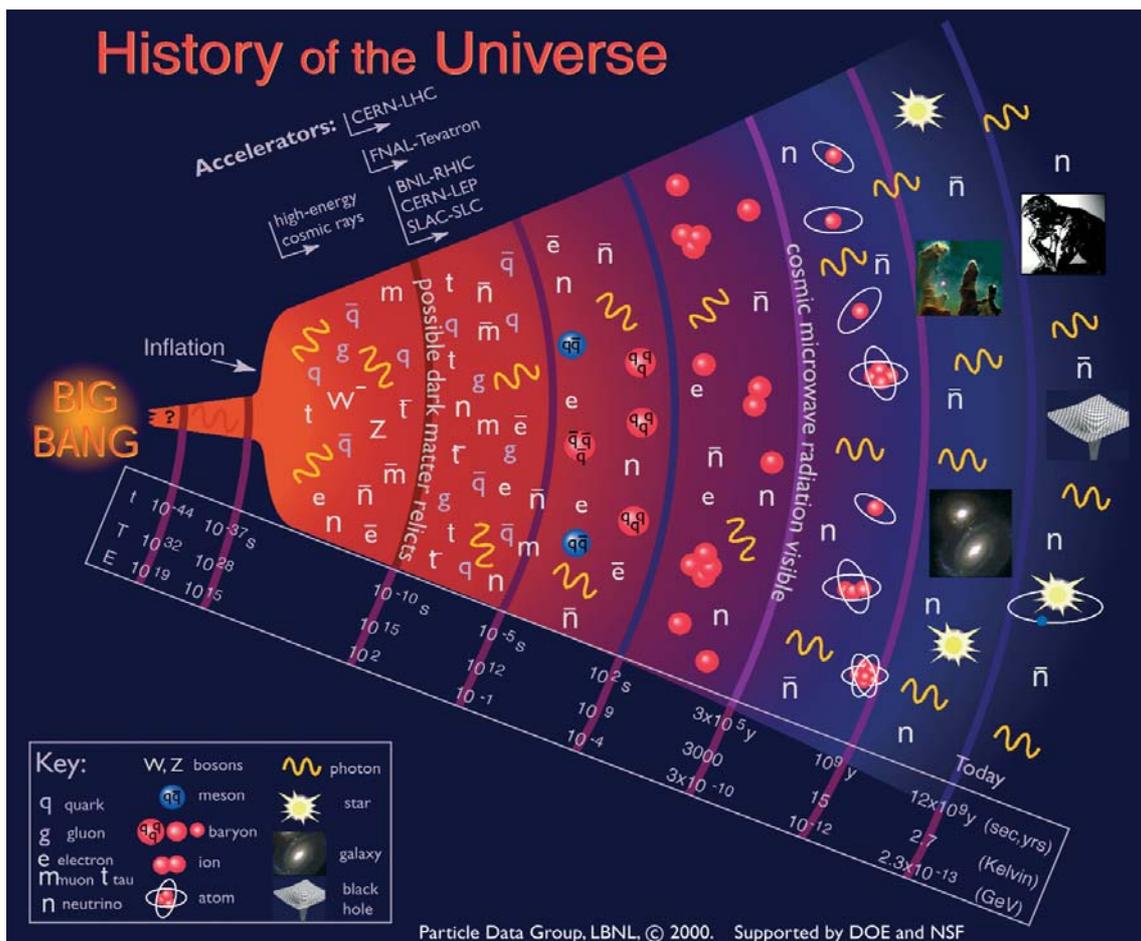


Figure 5.2: The evolution of our universe is strongly influenced by the gravitational interaction.

If small modifications in the gravitational interaction have to be applied, then all the astrophysical and cosmological data have to be re-interpreted and the whole history of our universe has to be written anew.

Source: Particle Data Group, LBNL, © 2000 (supported by DoE and NSF)

The orbital environment also allows for other “special features” such as large velocity differences or variations.

These space environment conditions can be achieved with a variety of techniques. Actually the most extreme conditions can be achieved only by free-flyers, some only on an interplanetary orbit.

The ISS is an ideal platform for those experiments where repeatability and modularity are a key issue.

5.1.4. Fundamental interactions and universal theories

This topic is obviously of paramount importance, starting with the origins of our universe and ending with its future (figure 5.2).

Discussing in detail all the key questions that are being and have been studied in the field goes beyond the scope of this report. Hence only a few outstanding cases will be briefly summarised.

5.1.4.1. The search for new long-range interactions

One of the outstanding questions in our understanding of nature is that two fundamental theories, namely quantum mechanics and general relativity – demonstrated by an enormous wealth of experiments – appear to be in contradiction. As the first theory is the basis of our understanding of three out of four known interactions, while the second is our model for the fourth, i.e. gravity, this inconsistency prevents the so called “grand unification” of fundamental interactions.

All theories trying to solve this paradox call new interactions into play. These interactions, weak and long range, would be superimposed on gravity, mimicking violations of Galileo’s principle of universality of free-fall, also known as the Equivalence Principle. The search for these forces demands a large mass source, for example the Earth, very pure free-fall conditions (purely gravitational orbit) and a very quiet environment. Space appears to be the obligatory way to go. Indeed all experiments proposed and studied in some depth are based on comparing the rate of fall of two bodies, nominally at the same location, due to their interaction with the Earth. In orbit, a difference in the rate of fall will result in a tiny relative acceleration of the two orbiting bodies that could be measured with a sensitive differential accelerometer. A similar concept that uses cold atoms instead of macroscopic bodies has also been implemented on the ground and proposed for a flight implementation.

Our models for *elementary interactions* become more and more entangled with our understanding of

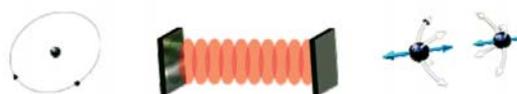


Figure 5.3: Atomic, optical, and molecular clocks:

Metaphorically speaking, the second defined by an atomic clock (left) is the time the electron needs to orbit the nucleus, the second defined by an optical clock or resonator (middle) is the time a photon needs to move back and forwards between the two mirrors at the two end/sides of the optical cavity, and the second defined by a molecular clock is the time for one vibration or one rotation. (The variety of definitions of clocks is even wider than given here.) Each of these clocks is based on different physical principles: while the first one is based on the motion of an electron, the optical clock is based on the motion of photons, and the last one on the motion of whole atoms. It is a remarkable but well proven principle of physics underlying Einstein’s theory of gravity that in gravitational fields each clock behaves in exactly the same way as the others.

Source: ESA (adapted from the report of the ESA Topical Team on “Fundamental Physics on the ISS”, May 2004)

the history and structure of the universe. A series of questions about the space-time validity of elementary interactions is tested via the time dependence of fundamental constants, something that can be done only with extremely precise clocks. Free-falling, high-precision atom clocks and hydrogen masers are the key instruments for these experiments. The approved experiment ACES will substantially advance the measurement precision of the time dependence of the fine structure constant, the key parameter of quantum electrodynamics, by comparing the pace of its cold atom clock PHARAO to that of the hydrogen maser (figure 5.3).

Quantum theory has been the realm of microscopic distances for a long time. The recipe for the measurement process in quantum theory, in addition to the concept of collapse of the wave function does not contain any explicit reference to space. Over the last decades quantum theory has progressively advanced into the meso- and macroscopic world thanks to macroscopic quantum condensates, first with superfluids and superconductors, and more recently with the Bose-Einstein condensation or degenerate fermionic quantum matter. In addition, in recent years experiments on entangled photon states, probing the foundation of quantum measurement and communication theory, have gained momentum. This experiment ranges from tests of Bell inequalities, to quantum teleportation, to tests of quantum entanglement over large distances.

For bosonic and fermionic *quantum matter*, gravitational and inertial fields play important roles in several respects. First, these fields couple adiabatically to quantum states, modulating their properties. This makes the gravitational fields the ultimate distur-

bance for these systems but also makes the same systems ideal detectors of those fields. This is the reason why in recent years many proposals have been made to test matter-wave interferometry in space and to use the interferometers as detectors of frame dragging and other gravitational effects predicted by Einstein's Theory of General Relativity. One of these proposals has been studied at system level by ESA as the Hyper mission, an orbiting matter-wave interferometer designed to map the frame-dragging field of the Earth.

Second, Earth's gravity forces experiment with cold atoms in general and Bose-Einstein condensates in particular to use levitation and confinement devices. The disturbance due to these devices prevents the condensate from reaching the ultimate low temperatures and prevents an increase in the size of the system. In space, due to the possibility of long-term free-fall, one should be able to reach femto-Kelvin temperatures, and open up a regime of new physics not obtainable on Earth.

Third, only in this very low temperature regime, is thermal noise effectively suppressed so that one can fully investigate the intrinsic limitations to quantum coherence in these macroscopic systems, for instance those due to the interaction with vacuum states or other fundamental disturbances (figure 5.4).

The 2001 Nobel Prize in Physics was awarded for the creation of Bose-Einstein condensates to E.A. Cornell, W. Ketterle, and C.E. Wieman, underlining how the physics community acknowledges the importance of this area of physics. And a prerequisite for these studies was and is the laser-cooling of the atoms – indeed it is the most important step in creating a BEC. The importance of this technique has also been emphasised by the award of the 1997 Nobel Prize in Physics to S. Chu, C. Cohen-Tannoudji, and W.D. Phillips.

Over the past few years, an impressive series of experiments has been performed in ground-based laboratories on *quantum entanglement*. Quantum theory predicts many different, apparently paradoxical results when the wave function of a system has a large spatial extension and measurements on the same system are made locally at different places. Some of these properties are now used for unbreakable encryption of messages over a communication channel. Quantum theory does not contain any prediction on the space-time limitation of these non-local correlation effects. Will the correlation eventually be lost, if some unknown fundamental de-coherence mechanism is acting on the wave function over long distances? Space is the only place

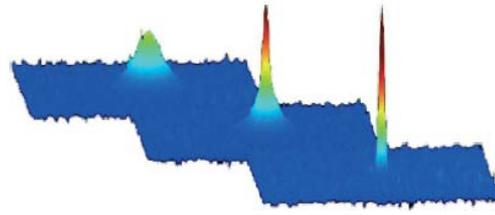


Figure 5.4: Bose-Einstein condensation.

If identical bosonic quantum systems are cooled down to very low temperatures (of the order of nK), then each individual system falls into the lowest possible energy state. As a consequence, all the wave functions of the individual systems overlap, and the whole system begins to become one single giant quantum state, the Bose-Einstein condensate. In this condensate all atoms are linked coherently, and they behave as a single quantum state with one phase.

Source: ESA (adapted from the report of the ESA Topical Team on "Fundamental Physics on the ISS", May 2004)

where these experiments, all currently based on photon states, can investigate large distances. On Earth, the fundamental limitation at $\approx 100\text{km}$ due to the surface curvature, absorption losses in the atmosphere and losses in optical fibre systems is being rapidly approached (figure 5.5).

5.1.5. Complex plasmas – a new state of (soft) matter

Complex plasmas consist of ions, electrons and charged microparticles. It was discovered experimentally that these systems can be strongly coupled, forming essentially new states of matter: liquid and crystalline plasmas. The microparticles are easy to visualise individually and hence complex plasmas provide a unique research opportunity to study self-organisation processes in liquid and crystalline systems, non-linear dynamics of (many-) particle systems, strong coupling phenomena in systems with rotational as well as translational degrees of freedom (for rod-like particles), critical phenomena, and universality concepts (see also the Condensed matter section 5.1.6), phase transitions, transition to turbulence, self-organisation and scaling behaviour in fluid flows down to kinetic (particle) scales – including the transition from discrete to continuous systems, classical nanofluidics, physics at, near and far from LTE in unmagnetised and magnetised states, etc. – at the most elementary, the kinetic level (measuring true distribution functions).

The available parameter range for such studies is huge; to mention only one example, liquid plasma systems can be engineered as a "one-phase fluid" as well as a "two phase fluid" if the conditions are suitably chosen. With the low damping (due to the background gas), the ability to investigate rapid processes

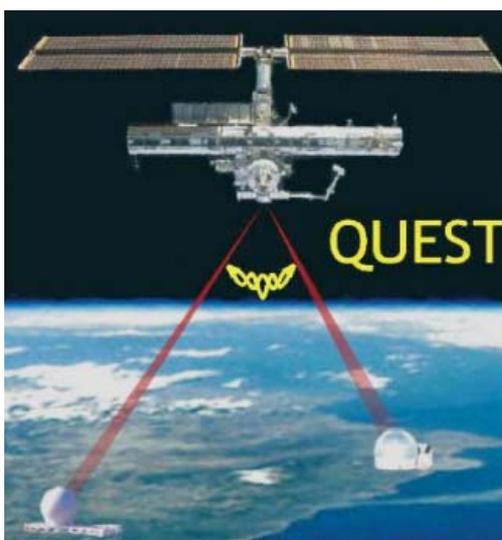


Figure 5.5. The QUEST proposal. The source for entangled photons is placed for example on the ISS, and the two photons are sent to two separate ground stations. The objectives of this experiment are to demonstrate, for the first time in space: (1) absolute secure global distribution of cryptographic keys from space, based on novel quantum communication techniques, and (2) fundamental quantum physics principles beyond the capabilities of Earth-bound laboratories by using the added value of space environment.

Source: ESA – General Studies Programme

(up to the dust plasma frequency), the diversity of systems available (for example, homogeneous, binary, anisotropic, stratified), magnetisation etc., complex plasmas occupy a parameter range for fundamental research that is not covered by any of the other neighbouring research fields such as complex fluids or granular media (figure 5.6).

5.1.5.1. Technology and the need for microgravity

In order to carry out research into complex plasmas, technological developments are necessary, including plasma chambers, particle diagnostics and manipulation (control) techniques. Research in this field will naturally be a technology driver. This is already happening in areas such as powder technology, plasma polymerisation, particle growth and surface coating, solar cell technology, plasma catalysis, plasma sterilisation technology etc. One of the key elements is always particle visualisation and control – these technologies will have already and will continue to provide spin-offs, and presumably many that we cannot even imagine at this time.

The need for research in space is obvious in this field. Since one of the important points of this new state of matter is the (effective) absence of a damping background medium, support against gravity

becomes a key issue. In the laboratory, this support against gravity can be achieved using electrostatic fields, magnetic gradients and/or thermophoresis. However, for experiments under “low stress” conditions it is essential to use microgravity.

5.1.5.2. Development of the field

• Publication activity

An analysis was made to establish the status of the field worldwide. This analysis was conducted by the Informationsvermittlung der CPT-Sektion, (Dr. Schier). To this purpose the field of “complex (dusty) plasmas” (as defined; for example, in PACS No. 52.27.Lw) was compared with the neighbouring fields in terms of the publication activity. The main results are as follows:

- 10 years after its beginnings (Thomas et al: 1994) the field of complex plasmas has developed a simi-

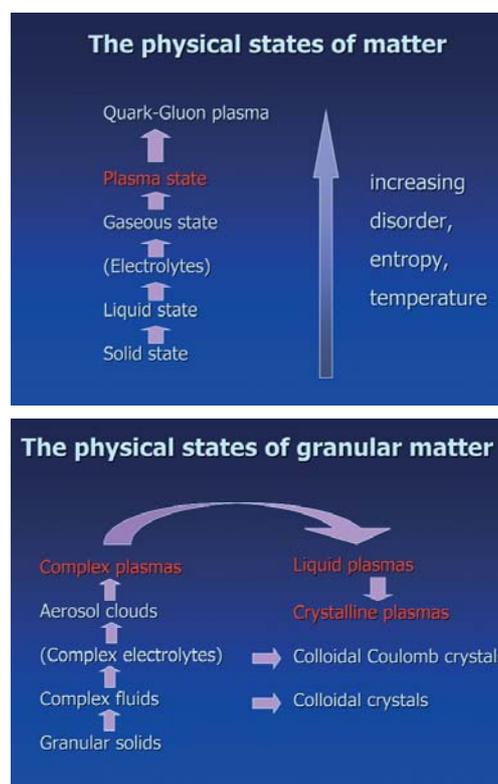


Figure 5.6. The top panel shows the states of matter, with increasing temperature or entropy. The “electrolytic state” is “thermodynamically open”, in the sense that the charged component has to be specially maintained by external energy sources (in addition to a “heat bath”). This is true also for low temperature r.f. plasmas ($T \ll 10^4$ K).

The lower panel shows the corresponding states for “complex” or “soft” matter. Complex electrolytes and complex plasmas are also thermodynamically open systems. Ten years ago it was discovered that complex plasmas can exist in liquid as well as crystalline states.

Courtesy: G.E. Morfill

larly high activity level as the neighbouring fields in soft matter physics.

- Complex plasmas are still growing.
- Total number of publications in the years 1995 to 2002 were 1 760, in 2004 the number is expected to reach 3 000.

The information is presented in Figure 5.7.

• Demography

A survey of research groups attending recent conferences on “complex (dusty) plasmas” was carried out. It was found that since 1994 over 100 research groups have taken up this field. The current demography is approximately:

Europe	25
USA	25
Russia/Ukraine etc.	20
Japan	20
China	10
Others	15

Some groups are experimentally oriented, some concentrate on applications and some are theoretically oriented. The demographic distribution reflects the industrial strength of the various countries.

5.1.5.3. Research examples

Some recent research highlights are described hereafter.

• Coalescence of complex plasma “fluid drops”

Experiments performed on the ISS have shown the deformation on approach that is due to a plasma sheath forming on the surface of the complex plasma cloud. Plasma sheaths usually form at solid boundaries. In this particular case the surface is extremely porous (only ~0.01 % is solid) but a sheath forms nonetheless (figure 5.8 and 5.9).

The field of complex plasmas has been fortunate inasmuch as it already has a working “laboratory” (PKE-Nefedov) on the ISS since 2001. Many discoveries have already been made, including the physics of discharging of plasmas and a new charge-induced runaway coagulation (gelation) transition that exceeds the well-known geometric rate by five orders of magnitude! The future for this field, with its great interdisciplinary potential, appears very promising indeed.

5.1.6. Condensed matter – universality and scaling

Systems consisting of many particles are described by statistical methods which serve as theoretical tools for the derivation of averaged properties that are accessible to experiments. Such properties are

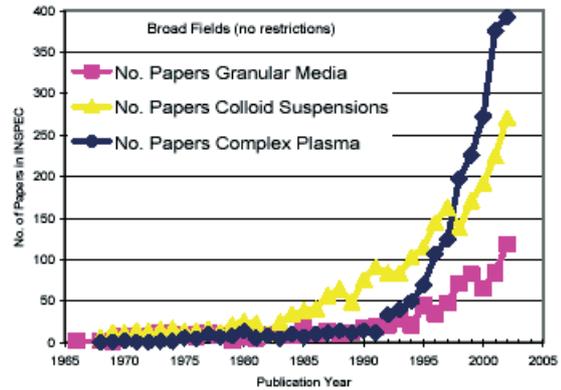


Figure 5.7. Publication rates in the three “soft matter” fields, granular media, colloidal suspensions and complex dusty plasmas (Dr. Schier, Stuttgart). The search references were “colloidal suspensions, colloid crystals, complex fluids”, “granular fluids, granular medium or media” and “complex or dusty plasmas, plasma crystals”.

Credits: Dr. Schier, CPT-Sektion, Stuttgart, Germany

temperature, pressure, specific heat, density, etc. The basic quantity underlying the calculation of these properties is the partition function from which all else can be derived. A method for the determination and analysis of the structure of the theoretical results is the renormalisation group theory, which also has applications in other branches of physics.

The main result of this theory is that critical phenomena (phase transitions) appearing through manipulation of parameters show universality and a certain scaling behaviour. The universal, scaled behaviour depends only on the space dimensionality D (generally 3, but it can be 2 for surface phenomena) and the dimensionality N of the order parameter (the parameter which breaks its symmetry at the transition). The couple (N, D) defines universality classes. The case $N=1, D=3$ corresponds to the gas-liquid critical point, where outstanding results have been obtained thanks to the space conditions of weightlessness. The ongoing programme is discussed in the fluid and interfaces section. The class $N=2, D=3$ corresponds to the superfluid transition. The critical temperature between the normal and the superfluid state of a system depends on the pressure. However, when we approach the critical temperature other thermodynamic quantities like the specific heat, the magnetisation, or the density, behave universally, independently of the pressure. This means that near the critical temperature certain quantities describing the many-particle system depend on the temperature alone. In these equations there is no reference to the actual system used. Therefore all systems must behave in the same way. This is a very surprising prediction.

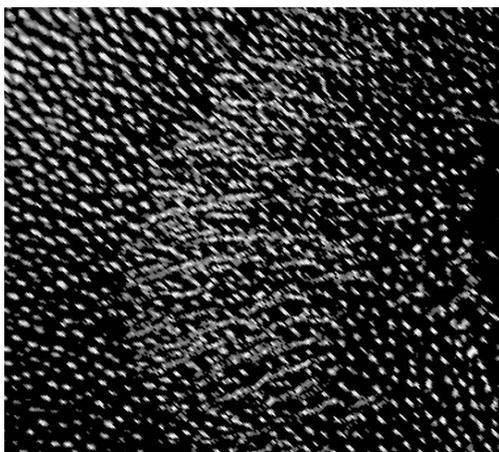


Figure 5.8. Self-organisation of counterstreaming complex plasmas. In normal plasmas one would expect the free energy due to the streaming to lead to instabilities which randomise the particle flow (velocity space instabilities). In strongly coupled systems, surprisingly, the flow self-organises into discrete interpenetrating streams, (a coordinate space instability). This appears to be energetically most favoured. (Experiment performed on parabolic flight).
Courtesy: G.E. Morfill

Another issue in condensed matter physics is that the behaviour of many-particle systems should also depend on the size of the system. However, once again, the functions which are thought to depend on size are actually found to be independent of size. Again, we have a universal behaviour for these systems.

Superfluid Helium ^4He is best suited to an experimental study of these predictions of statistical physics, and renormalisation group theory. And many experiments have been carried out using superfluid Helium ^4He on Earth. However, gravity induces inhomogeneities in the system which greatly limits the attainable accuracy of these terrestrial results.

There is another very interesting development, destined to bring progress to this interesting and important field in fundamental physics from a very different direction: complex plasmas. If the interparticle forces in complex plasmas have an attractive component, as predicted by theory, then kinetic measurements at the gas-liquid critical point could be possible – thus providing information at the most elementary (the individual particle) level for the first time, a truly exciting vision for condensed matter physics.

The 2003 Nobel Prize in Physics was given to Alexei A. Abrikosov, Vitaly L. Ginzburg and Anthony J. Leggett for their research on superfluidity and superconductivity.

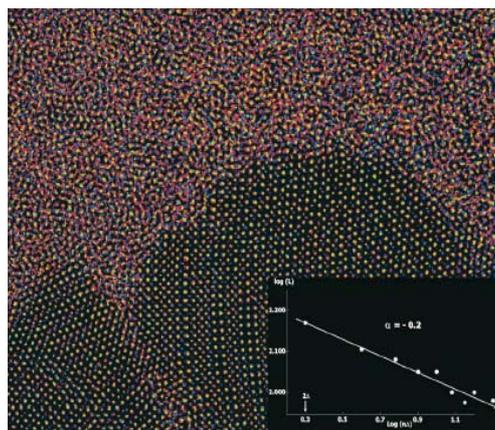


Figure 5.9. Development of crystallisation fronts. A complex plasma on Earth may crystallise, with the crystallisation front moving upwards. The liquid state in this example is at a much higher temperature than the crystalline state (non-equilibrium crystallisation). Even at the kinetic level we see that dendritic-like structures appear with a linear fractal dimension of 0.2 all the way down to single particle distances (2Δ), as well as thermally excited thin domain boundaries. (Experiment performed on Earth).
Courtesy: G.E. Morfill

5.1.7. Complex systems – atmospheric and cosmic particles

The most important “complex system” for humanity is our environment. There are many detailed interacting processes that play a role, in a complex and often non-linear function, to determine climate, ocean, land and atmosphere evolution. The influences extend from outside our planet – space – to internal ones produced by humankind itself. The planned ICAPS facility (part of the IMPACT, International Microgravity Plasma Atmospheric and Cosmic particle Twin-laboratory) addresses some of the outstanding fundamental physics issues in this field; for example:

- How do aerosol and airborne particles affect climate and weather?
- Why do clouds and precipitation cleanse particulate pollutants so efficiently from the atmosphere?
- How do particles agglomerate?
- What is a regolith and how does it evolve?
- How do planets form?

By simulating primitive and small solar system bodies – a major part in the ICAPS programme – fundamental properties of these objects will be known by the time of Rosetta’s encounter with comet 67P/Churyumov-Gerasimenko in 2014.

5.1 7.1. The scientific programme of ICAPS

ICAPS research is sub-divided into so-called Central Research Topics (CRTs). The main scientific objectives of these CRTs are:

- **CRT1 – Aerosol microphysics.**

The International Panel on Climate Change (IPCC) has repeatedly emphasised that the uncertainties with respect to radiative forcing are much larger for aerosols than for greenhouse gases, and for both of them the anthropogenic contribution is by no means negligible compared with the natural one. Remote sensing by satellites and computational efforts have led to impressive improvements in understanding but experiments are still necessary, and some of them can be performed only under microgravity conditions. This is because clouds consist of droplets with a wide size spectrum and very different settling speeds, which cannot be studied simultaneously under laboratory conditions, and certainly not for atmospherically-relevant times. Therefore, cloud physical aspects form the main topic of CRT1.

- **CRT2 – Phoretic effects**

Among the plethora of forces (gravity, frictional resistance, thermo-diffusiophoresis, electrostatic), the phoretic effects are the most-influenced by sedimentation of the hydrometeors and the consequent deformation of temperature and vapour fields, an effect which should be absent under microgravity, and allow detailed studies to be made.

- **CRT3 – Dust agglomeration.**

Coagulation played an important role in the formation of the planets of our solar system, and hence laboratory experiments on dust agglomeration are essential. However, due to gravitational settling such experiments are severely limited. Under microgravity conditions, the experiments can be more controlled (for example, Brownian motion, motion induced by photophoresis, or motion induced by differential charging of the grains) over durations exceeding one hour. With these experiments, it is expected to observe dust agglomeration over an extended size range, from small micrometre-sized grains to centimetre-sized agglomerates. For the characterisation of the dust agglomerates and for the determination of their mass spectra, digital long-distance microscopy as well as multiwavelength, multiangle light scattering will be used. From these observations, a deeper insight into the light-scattering behaviour of irregular particles is expected.

- **CRT4 – Simulated regoliths**

The surfaces of most solar system objects are covered by a so-called “regolith”, or layers of usually loosely-connected fragmentary debris produced by, for exam-

ple, meteoritic impacts. Regolith formation and evolution depends upon the gravity level of the planetary body and the mechanical properties of its constituent particles and aggregates. The latter properties are poorly known for most of the small bodies in the solar system. The part of the ICAPS programme dedicated to regolith studies can be divided into two main subjects: (1) morphological, mechanical, thermal, and electrical properties; and (2) optical properties. The aim is to gain a better understanding of regolith formation and evolution processes of small solar system bodies and to provide input to models and ground-based experiments developed to prepare upcoming and future landing and sampling missions on asteroids or comets. Linking the physical parameters of the regolith with parameters obtained by means of light scattering should be valuable for interpreting remote sensing data of small solar system bodies and for classification aspects, and are therefore considered as key experiments in solar system physics.

- **CRT5 – Light-scattering experiments.**

With only a few insitu studies and sample returns, information about physical properties of dust in the solar system is obtained mostly from remote light-scattering observations. To interpret such observations in terms of physical properties (for example, morphology, size distribution, porosity, and albedo) of the dust particles, aggregates and regoliths and to guarantee the uniqueness of the solution, particle separation by sedimentation or gravitational compaction must be avoided, and light-scattering experiments must be performed on realistic analogs of the scattering dust or regolith. The ICAPS light-scattering unit will operate from near-backscattering to about 170° forward scattering using three wavelengths (from optical to near-infrared) and will provide a unique approach to deduce, without ambiguity, the physical properties of dust particles, dust clouds and regoliths in the solar system and in other astrophysical environments from their observed optical properties.

A future generation of ICAPS experiments will be dedicated to research on small particles consisting of frozen gases (“ice”). Research on icy particles spans key hot topics in astronomy and atmospheric sciences, for example, star formation, cometary science, origins of life, cloud formation (including polar stratospheric and cirrus clouds), Earth’s radiation budget, and radiative forcing by nanometre-sized ice particles and aerosols in the atmosphere (figure 5.10).

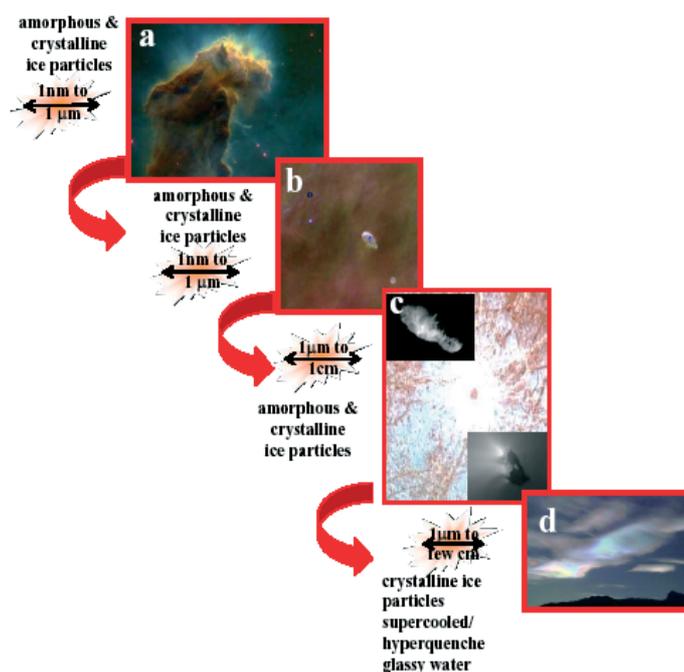


Figure 5.10: The evolution of icy particles from the interstellar medium to planetary atmospheres, showing the key water ice phases and grain sizes at each stage. (a). Icy mantles form on dust particles in interstellar clouds, through sublimation from the gas phase, or reactions on the grain surfaces. (b). As dense cores within interstellar clouds collapse, forming a new star, icy grains are incorporated in the coldest regions of the disk. Closer to the “baby” star, icy mantles are evaporated and reform as the disk cools. (c). Over a few million years, dust particles in the disk collide and aggregate, forming small planetesimals, which eventually form planets. Planetesimals that fail to form planets might remain in the new solar system as asteroids, the surfaces of which are later covered with regolith. Temperatures are sufficiently cold that icy regolith could feasibly be found on the surface of such objects. For distances to the protostar greater than those corresponding to the ‘snow line’, icy particles may aggregate to form icy bodies, such as cometary nuclei and Kuiper Belt Objects. (d). Many planets and moons within our own solar system are known to have ice on their surfaces and in their atmospheres. On Earth, icy particles are known to form in various clouds from water vapour and supercooled liquid water. These icy grains are a key constituent of polar stratospheric clouds, that themselves play a major role in the chemistry of our upper atmosphere.

Credits: (a) Jeff Hester and Paul Scowen (Arizona State University), NASA; (b) D. Johnstone (CITA), J. Bally (University of Colorado) et al., WFPC2, HST, NASA; (c) PIRL, Galileo Project, NASA, Halley Multicolor Camera Team, Giotto Project, ESA, Deep Space 1 Team, JPL; (d) P. Newman and R. Kawa

5.2. Physics of fluids and interfaces

Highlights

- Observation of a clustering transition in granular matter under vibration; relation to the accretion of matter in the cosmos (published in *Physical Review Letters*; commented in *Science* and *Nature*; bronze medal of CNRS)
- Discovery of a new thermalisation mode in compressible near-critical fluids (French Academy of Science award)
- 2001 Edmond Brun Prize awarded by the French Academy of Sciences for scientific achievements on foam dynamics.

5.2.1. Introduction

In this field of research we consider the behaviour and handling of fluids and fluid mixtures under space conditions. Furthermore, fluid physics plays an important role in other essential parts of space research, including the life sciences (for example, hydroponics, life support systems) and materials science (for example, solidification). Combustion has been considered a part of Fluid physics, as has been foams and granular materials. On Earth our personal experience with fluids is strongly conditioned by the presence of gravity. For instance, we observe that a gas expands to fill its container, while a liquid stays at the bottom of an open vessel: this is not true under weightlessness.

In nearly all scientific investigations and engineering applications in space, the behaviour and handling of fluids pose new and unforeseen questions, as does their practical management. These questions arise not only in questions of basic science (life science, materials science, fundamental physics) but also in engineering science and technological solutions (propulsion, heat exchangers, cryogenics). Conventional models of fluid flow, such as the Navier-Stokes Equations, still apply in space: but the relative importance of imposed forces changes dramatically, as do the boundary conditions. Thus entirely new and often unexpected solutions arise.

Topics, which are especially well represented in European fluid physics research include:

- fluid flow with external body forces imposed (vibrations, electric or magnetic forces);
- phenomena at the interface with a solid (capillarity and wetting, thermal transport, phase changes, particularly boiling or condensation);
- complex fluid systems (foams, films, emulsions);
- chemistry and combustion;
- fluids at supercritical or near-critical pressure and temperature.

Priority areas for the next four years, defined as research areas that can benefit not only a particular user community, but also promise advances in several other application fields have been identified as

follows: (1) high pressure and supercritical combustion; and (2) boiling and boiling crisis. Both of these topics are of high interest for both fundamental science and industrial applications.

5.2.2. Fluids with imposed, external body forces

On Earth the behaviour of all fluids is strongly affected by gravity. The effects of external fields (electric, magnetic, driven vibrations, thermal gradients) may be difficult to distinguish in the presence of strong gravitational effects. A low gravity environment provides a unique opportunity to remove the strong limitation that this places on terrestrial experiments, whether aimed at fundamental or applied science.

One example of such flow is the scale model study of the Earth's core and mantle, involving both gravity and apparent forces (Coriolis, centrifugal). Such a geophysical system can be realised on a much smaller scale, mimicking these forces using electric fields. Another example of immense practical importance is the management of fluids in space, for example in tanks or transport systems.

5.2.3. Phenomena at the interface with a solid

Under low gravity conditions the relative influence of boundaries can increase greatly and become very important for its equilibrium state and the transport processes. The phenomena presently under study are the following:

5.2.3.1. Capillarity and wetting

The typical size at which gravity effects are cancelled by capillary forces is the capillary length $l = \sqrt{\frac{\sigma}{g\delta\rho}}$, where σ is the gas-liquid surface tension, $\delta\rho$ is the gas-liquid density difference and g the gravitational acceleration. Under terrestrial conditions, the capillary length of an air-water interface at room temperature is about 3mm, hence capillary effects always dominate at small scales. There is a noticeable exception at the gas-liquid critical point, where the interfacial tension vanishes (the density difference also goes to zero, but with a less power). At low gravity, however, the length scales at which capillary effects become important are much larger. The weightless world is thus a re-scaled micro-sized world. Management of fluids becomes markedly different in orbit, with a strong influence of wetting conditions and contact angles.

Some devices that cannot work on Earth can thus be used as heat pipes with capillary flows. This poses

also questions regarding phase transition at the microscale, a problem of microfluidics that receives much attention for other reasons in ground-based industry.

5.2.3.2. Thermal transport, phase changes (particularly boiling or condensation)

Heat transfer technology lies at the heart of current demands for better energy and environmental policies. Thermal transport on Earth is mainly governed by convection (natural or forced). The suppression of gravity cancels the natural convection; the convective structure of flows becomes much different.

Heat exchange by phase change (condensation, boiling) is very efficient because of the latent heat that is involved in the process. Nucleate or flow boiling is thus widely used in the heat exchangers, however, with large safety factors. This is due to the so-called boiling crisis. When the heat flux is increased too much, vapour bubbles that would normally detach from the heater surface, have a tendency to spread out to create a vapour film, preventing an efficient heat exchange. The temperature of the heater increases until burnout.

The exact nature of the boiling crisis is still under debate. Performing experiments near the gas-liquid critical point is valuable because the surface tension vanishes, so other forces will become dominant. At present, technical applications employ empirical correlations for heat exchanger layout, all developed from experimental data taken under terrestrial conditions, which include a buoyancy force. Reliable data are missing for lower gravity conditions. This is especially relevant for instance in the re-ignition process of cryogenic engines in orbit (Ariane 5), for which the cryo-pumps must be cooled using heat exchanger units.

5.2.4. Complex fluid phase: foams, films emulsions

Foams and emulsions have properties largely governed by the surface tension associated with the interface between the two phases, but gravity intervenes to cause drainage and separation in most cases. A weightless environment can extend the range of realisable systems greatly. One particularly interesting case is that of metal foams (see section 5.3 on materials physics) which collapse before solidification in the terrestrial environment, except for very special compositions. Thus foams of remarkable structure and strength can be demonstrated under low gravity conditions.

5.2.5. Chemistry and combustion

Combustion is normally accompanied by very large density changes and consequent buoyancy forces that induce natural convection flows. It is therefore radically different in space, where mass transport is mainly driven by diffusion. One typical example is the case of laminar burning around single droplets that without gravity becomes symmetric. Another aspect of combustion is safety: how will a fire spread in a satellite or a space station? The study of combustion properties of materials aims to understand the influence of microgravity and convective flow on the flammability of materials.

Soot and particle formation is also an important topic in microgravity relating to droplet and spray combustion. Due to the absence of buoyancy, microgravity experiments offer the possibility of simple experimental conditions (homogenous cloud of droplets, larger droplet diameter) for a more systematic model validation. The combustion of complex metal particles aims to investigate the metal particle combustion in CO_2 for future Mars missions.

All studies have a significant potential of application. Droplet evaporation and combustion under transcritical conditions could be useful in applications to various high pressure systems such as diesel engines, gas turbines, aero-engines and especially rocket propulsion, where oxygen evaporates under supercritical conditions. High-pressure combustion research is not yet common, but fundamental data obtained on the ground or under microgravity conditions is of general interest for a broad range of applications.

5.2.6. Supercritical phenomena

Near-critical fluids are fluids near their critical pressure and temperature, at which gas, liquid and solid may coexist. They are very sensitive to density and temperature changes: their thermodynamic parameters (specific heat, compressibility, thermal expansion) and transport coefficients (thermal diffusivity) vary strongly in the vicinity of the critical point.

Because of these anomalies they are also very sensitive to gravity. On Earth, buoyancy-driven flows are impossible to avoid, and they obstruct our efforts to understand other basic transport mechanisms. The very large compressibility of the near-critical fluid entails significant gravity-induced density gradients and sedimentation.

The microgravity environment of an orbiting platform is ideal for the study of such systems; in particular, it has permitted the discovery of the Piston Effect, a very efficient way to thermalise such

compressible fluids, and further discoveries may be anticipated.

Present studies on fluids near the critical point are aimed at some fundamental features such as (1) the observation of density fluctuations (the order parameter of the phase transition), and (2) heat transfer by boiling and the onset of boiling crisis. Microgravity can prevent heterogeneous nucleation and enable homogeneous nucleation to be studied.

Supercritical (SC) fluids are fluids at temperatures and pressures above the critical point. They exhibit liquid-like density and gas-like viscosity and mass diffusion, thus promoting very fast and efficient chemical reactions and good solvent properties. These characteristics make these fluids increasingly useful to industry as non-polluting solvents of organic materials (for example, SC CO_2) and media for high-yield chemical reactions. Examples are found in incineration of organic chemicals in SC H_2O , the production of nano- and micromaterials for the electronics and drug industries. Removing gravity-induced flows would permit an understanding of the role of hydrodynamics in key issues such as the dissolution process of organic oils and the characteristics of nano- and micromaterials, a major topic where until now only the trial-and-error method has been used. A field at the frontier with combustion should be noted: cold combustion without gravity-driven advection, as in the usual combustion process, but with the specificity of SC fluids, where coupling is expected with the Piston Effect.

5.2.7. Granular materials

While the description of fluid systems can be approached using both hydrodynamic theory or by way of statistical thermodynamics, the description of granular media in terms of continuum mechanics or statistical mechanics still remains an open question, and seems to depend strongly on the flow regimes involved.

An “effective” temperature can be given to the granular matter by applying mechanical vibrations or alternating accelerations: a kinetic energy is then given to the grains that interact by inelastic collisions. The possible states that such a “dissipative” matter can assume are mostly unknown and pose many questions. This is particularly interesting as the accretion of dust in the cosmos should obey the same laws.

Many industrial processes make use of both the transport of granular media and their segregation/sedimentation into binary mixtures, for example, pharmaceuticals, cements and explosive/propellant powder preparation. Research of granular material

under weightlessness attempts to investigate fundamental properties, behaviour and control of such systems, with a goal of implementation in such industrial applications.

5.3. Materials physics

5.3.1. Introduction

The topic “materials physics” is concerned with the synthesis, structural and property characterisation of materials, their theoretical modelling from the nano- to the macroscale, the optimisation of their physical properties and their application to industrial products. As such, the top level objective is Innovating Technologies and Processes. Europe has a strong and leading role in the field of materials science and engineering in general and, in particular, constructing complex and multifunctional space equipment, scientific analysis of materials processing in space and new materials for space.

The physical properties of engineering materials, such as mechanical strength, creep and wear resistance, ductility, as well as magnetic and electronic characteristics are determined by the nano- and microstructure, chemical composition and type of defects produced during the synthesis process, for example during solidification from the melt. Besides the atomic scale inherent to condensed matter and the intermediate scales associated with the solidification microstructures, fluid flow driven by gravity generally occurs in the melt at the macroscopic scale of a cast product so that the relevant length scales in a

casting are widespread over 10 orders of magnitude, from the atomic size (capillary length, crystalline defects such as dislocations, attachment of atoms etc.) to the metre size of the ingot (fluid flow, spacing of dendrite sidebranches). It follows that for high precision castings the structural control during the liquid-to-solid phase transition is absolutely crucial for quality control and the design of advanced materials for specific technological applications. Therefore, the application potential of the materials physics area of research can be considered to be very strong.

On this basis, materials physics is closely related to fluid physics and to some extent to fundamental physics, and these days can be considered as nano-engineering, i.e. designing new materials from the nanoscale up.

The production and fabrication of alloys together with the casting and foundry industry generate a considerable amount of wealth, also within Europe. As such, this area of R&D constitutes a major backbone to European industry. The continuation of wealth generation in Europe by these industries relies on the improvement of its competitiveness with the US, Japan and others in the design and production of materials, for example in aerospace, automotive, biomedical, energy conversion and microelectronics. On this basis, the quantitative numerical simulation of casting and solidification processes is increasingly demanded by manufacturers. It provides a rapid tool for the microstructural optimisation of high quality castings, in particular where process reliability and high geometric shape accuracy are important (figure 5.11).

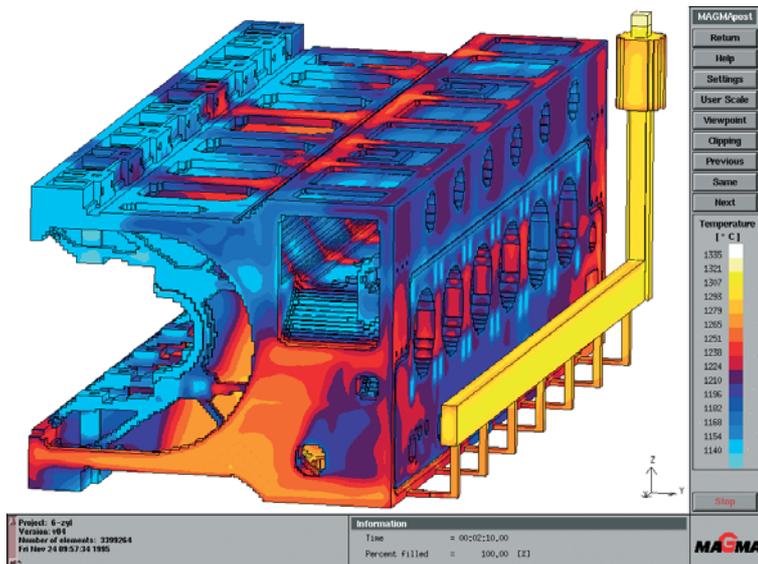


Figure 5.11. Cast structural components and the temperature distribution during casting of a complex engine block.

Courtesy: ThermoLab, by permission of MagmaSoft

Any improvement of numerical simulation results in an improved control of fluid flow and cooling conditions that enables further optimisation of the defect and grain structure as well as stress distribution at critical patches of components. Moreover, through the control of unwanted crystallisation events it becomes possible to produce even completely new materials with a controlled glass-like or nanocomposite structure.

5.3.1.1. Fundamental issues and applications

- theory of high temperature melts including thermo-physical properties
- liquid undercooling/nucleation
- solidification (crystal, glass, composite, metallic foams)
- pattern development
- self organisation
- multiscale analysis (nano to macro)
- high-speed computing

5.3.1.2. Potential applications

- casting processes (Fe-, Ni-, Ti-, Al-, Mg- alloys, refractories, MMCs)
- crystal growth of poly- and single-crystalline materials (turbine blades and discs, semiconductors, oxides)
- glass production/wires/fibres (metallic and non-metallic)
- rapid prototyping
- spray forming and powder production
- surface modification by spraying techniques

5.3.2. Space relevance

In this context, the specific environment of microgravity over long periods that can be achieved on board the International Space Station (ISS) has repeatedly proved of value in providing experimenters with a unique complementary way to get rid of the complex distorting effects of fluid flow driven by buoyancy in liquid and gas phases. In this way the unambiguous benchmark data needed to discriminate sound three-dimensional models within the diversity that is proposed for solidification and casting processes can be obtained.

In order to achieve the major goals set within the current programme two cornerstones have been identified:

Cornerstone 1. Thermophysical properties of fluids for advanced processes

Thermophysical properties of fluids for advanced processes that are required as input parameters for

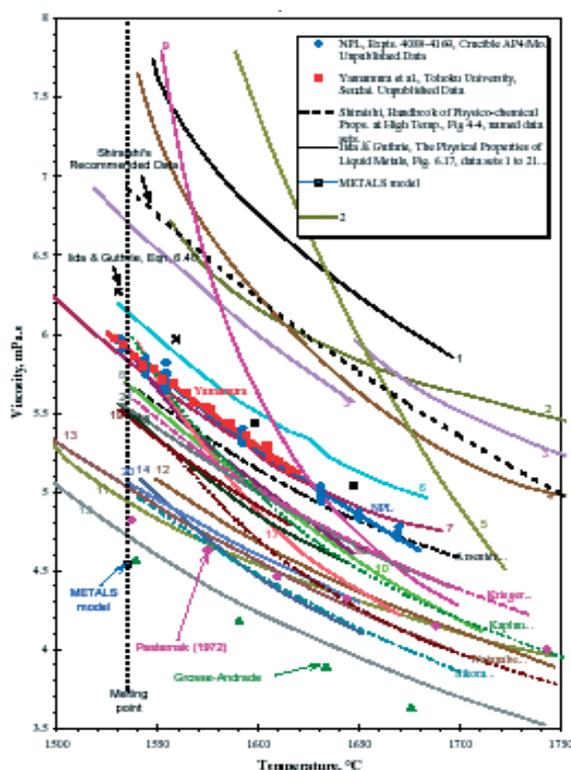


Figure 5.12: Viscosity of “pure” iron as a function of temperature as given in the literature. It can be clearly seen that the scatter of data is about 50%, and in other cases can amount to 100%

Courtesy: ThermoLab

adequately describing balances in volume phases (heat, chemical species, momentum etc.) and at interfaces (solid-liquid, liquid-gas etc.)

The paucity of thermophysical property data for commercial materials is a result of the experimental difficulties arising at high temperatures (figure 5.12).

The knowledge of these properties is essential for the understanding and subsequent modelling of materials-processing technologies. Thus, accurate input data are needed in the stable liquid and at different levels of liquid undercooling for a full and accurate analysis. Here the fundamental understanding of fluid flow and heat flow which are controlled by the thermophysical properties of the melt are key issues, also for the active control of industrial processes.

Besides the general importance of the thermophysical properties of multicomponent alloys for the control of industrial casting processes, the accurate knowledge of such data is also relevant for fundamental science (simple liquids, binaries etc.). For example, the analysis of phase transformations, fluid stability and dynamics, fundamental laws like dendrite and pattern formation as well as fundamen-



Figure 5.13: Levitation processing of a liquid metallic sample in 1g, resulting in a non-spherical geometry.

Courtesy: ThermoLab

tal studies of kinetics, transport and structure formation in physics, microbiology and geophysics require the accurate knowledge of the thermophysical properties controlling such processes.

High-precision measurements on chemically highly reactive melts at the temperatures of interest require the application of containerless processing using non-contact diagnostic tools. By eliminating the contact between the melt and a crucible accurate surface nucleation control and the synthesis of materials free of surface contamination become possible. Based on recent experience in a number of space shuttle and parabolic flight experiments, electromagnetic levitation (EML) including sophisticated analysis tools, has been developed and established as a versatile and reliable technique in studying highly reactive metallic melts. This technique offers several advantages over alternative levitation methods due to the direct coupling of the electromagnetic field with the sample. The required high accuracy can however be achieved only when the following conditions are fulfilled:

- extended periods of processing time (> 10000 sec.)
- ultra-high vacuum conditions (better than 10^{-8} Torr)
- minimised levitation forces and thus controlled heating and reduced liquid convection in comparison with 1g gravity conditions on Earth and
- sophisticated analytical tools.

The strong reduction of positioning forces and the shape optimisation to a perfect sphere in microgravity leads either to a significant improvement of the accuracy of the measurements or makes the measurement possible at all (figure 5.13).

A space experimentation system (MSL-EML) is under development for this purpose. In the future this will allow considerable improvements of existing materials processing technologies as well as the development and application of new advanced materials, such as glassy supermetals and other light-weight/high-strength materials with controlled micro- and nanostructures (figure 5.14).

• *Theory of melts*

Some important research topics are:

- SORET effect (oil recovery)
- understanding of mechanical bending in dendrites (lack of rheological thermophysical data)
- magnetic fluids
- terrestrial structural studies

• *Industrial needs*

A comprehensive survey was conducted among European industries involved in the production, refinement and use of metallic, often complex alloys. The survey included primary metal producers, secondary refinement and alloy production as well as end-users. This questionnaire has indicated the urgent need for high quality data of thermophysical properties. This need is fuelled by the increasing sophistication of the production process and product design brought about by the progress in the numerical

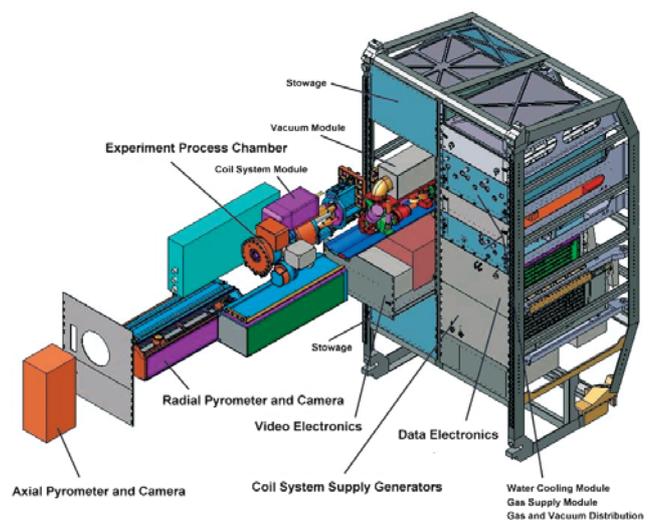


Figure 5.14: The planned electromagnetic levitation facility in the materials science laboratory on the ISS.

Source: ESA

modelling of casting and solidification processes as well as by the progress in the physical understanding of the basic processes involved (figure 5.15).

Cornerstone 2. New materials, products and processes

In order to develop new materials with particular functionalities and, as a result, new products, new or improved processing techniques are generally required, in particular, for the reliable processing of liquid complex alloys. Examples which are at the core of the scientific programme are shown in Table 5.1.

On the basis of the newly developed analysis and measurement techniques for the relevant thermophysical properties as described in Cornerstone 1, new processing technologies and optimised by computer simulation are being developed under Cornerstone 2 of the programme.

On this basis, a scientific programme has already been established within the MAP activity which includes the following topics:

• *Crystal nucleation and growth transients*

Transient stages, during which new phases may form and new patterns begin to develop, play a central role. During processing from the melt, for example for casting, welding, single crystal growth and directional solidification, crystal nucleation and growth is in most situations the first step achieved by cooling of liquid below its thermodynamic equilibrium solidification (liquidus) temperature to form crystalline nuclei of nanometre dimensions that subsequently grow. Alternatively, when the formation of nuclei fails, formation of a metallic glass occurs at the glass transition temperature. At this stage, the main limitations to a deeper understanding come from the lack of precise values of the thermophysical properties.

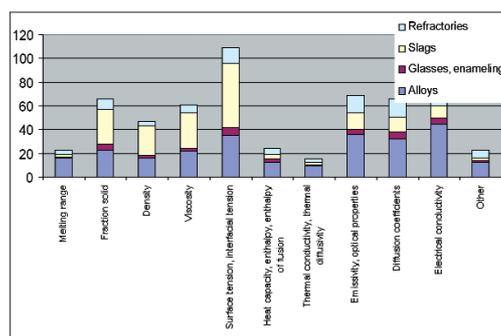


Figure 5.15: Industrial survey of over 300 European companies, showing the relevance of accurate knowledge of thermophysical properties for a range of different materials. Courtesy: ThermoLab

• *Columnar/equiaxed growth*

Directionally solidified superalloy turbine blades that are commercial cast-to-shape products contain columnar dendritic crystals. The mechanical performances of these blades depend on the fineness and regularity of the dendrite array, and rapidly deteriorate if dendrite misalignment, parasitic nucleation of new grains or freckling induced by severe solute-driven convection occur during casting. For the future single-crystal generation of turbine blades these requirements are becoming even more severe (figure 5.16).

The development of a thin equiaxed grain structure, homogenous in all directions, offers a convenient way of fulfilling the requirements whenever the production of a non-uniform material with dispersed properties should be avoided, such as in the investment casting of engine blocks for automobile industry. In practice, grain sedimentation is commonly observed on the ground. This prejudicial effect is suppressed in a low gravity environment where samples with a fully regular equiaxed microstructure are obtained.

Table 5.1: New materials and products and the relevant industry

New material	New product	Industry
Single-crystal nickel-based superalloys Gamma - Ti-Aluminides	Aerospace turbines with higher fuel efficiency and reduction of NO _x release Low-weight turbine blades	Aerospace
Al-, Mg-, Fe-base	Engine parts	Automotive
Ti-Al-base	Body replacement parts	Biomedical
Ni-, Ti-Al base	Land-based turbines with improved efficiency	Energy conversion
Ni-Al base	Fuel cell catalysts	
Cu-base	Leadframe materials	Micro-electronics
In-Ag-Cu-base	Lead-free solders	

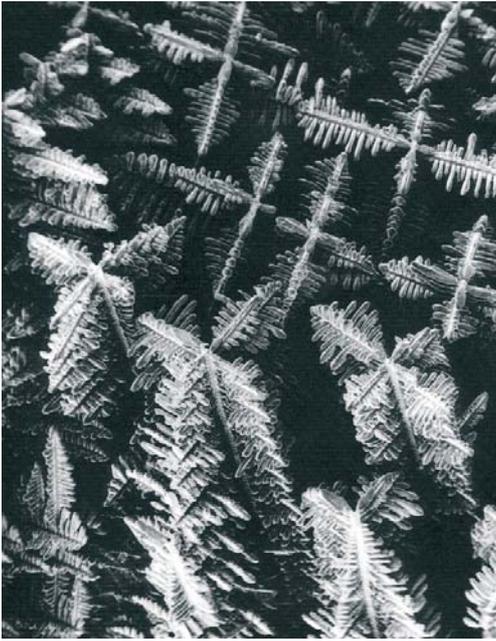


Figure 5.16: Columnar dendritic growth in a complex alloy
Source: ESA, courtesy H.J. Fecht and B. Billia, ed.: Seifert

• *Multiphase growth – multicomponent alloys*

The most common case of multiphase growth is certainly the solidification of binary and ternary alloys around the eutectic composition, where coupled growth of lamellae or rods of different solid phases is observed. These eutectics are the simplest natural composites but their use; for example, in electrical devices, is prohibited by the problem of the microstructure defects (for example, connected lamellae) which seems hard to overcome. Yet, some systems may present interesting mechanical properties, for instance by introducing fragile but high-strength rods into a ductile matrix.

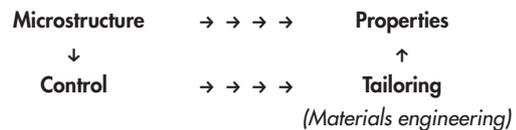
Monotectic patterns in which rods of a second liquid phase form together with a solid matrix are eutectic's cousins. The major difference is the presence of a number of fluid-fluid interfaces that are known to be prone to strong surface tension-driven convection. This phenomenon, which is generally of secondary importance on Earth where buoyancy-effects most often dominate fluid flow, is exalted in space where it can be studied pure and acting alone. Furthermore, monotectic systems with concentrations in the liquid miscibility gap, where droplets of the second liquid phase form in the melt, already have a potential application as car bearings when, once solidified, the droplets provide lubricating soft inclusions (Pb, Bi etc.) in a hard matrix.

• *Non-equilibrium undercooled liquid processing and glass formation*

When crystal nucleation can be avoided completely over the entire range of the under cooled liquid, below the liquid's temperature, the liquid eventually freezes to a non-crystalline solid – a glass. Glass has been manufactured from silicon and related oxides for thousands of years. More recently, by developing new alloys and processing techniques it became possible to produce more and more materials in an amorphous form. These have superior properties in comparison with their (poly) crystalline counterparts including materials with covalent (Si-based), van der Waals (polymers) and metallic bonding. In particular, new metallic glasses/supermetals which can be produced in large dimensions and quantities now, so called “bulk metallic glass” or “supermetals”, are becoming an important industrial and commercial material, superior to conventional Ti, Al- or Fe- based alloys.

• *Computer simulation of patterning and microstructure formation*

On the basis of the thermophysical property measurements outlined under Cornerstone 1 and the nucleation and growth analysis being undertaken under Cornerstone 2 a further optimisation of materials properties is being implemented by modern high-speed computer simulation as schematically shown below.



The ultimate challenge is the tailoring of the dendritic grain structure and segregation of chemical species formed at the scale of the whole casting during the solidification process together with the fine microstructure and microsegregation of the grains. In order to achieve reliable microstructure relationships, pattern formation in solidification processing is investigated under diffusive conditions and with fluid flow in the melt by means of comparative experiments, often accompanied by modelling, on model materials carried out in a simplified configuration suited to the physical effect(s) under focus.

Protein crystallisation (biological macromolecules). This topic is also addressed in the chapter on life sciences, section 6.2

Growth of non-metals, semiconductors (Si, CdTe and derivatives).

5.3.3. The IMPRESS project: new industrial materials with the help of space research

The ESA-led IMPRESS project (Intermetallic Materials Processing in Relation to Earth and Space Solidification) has recently been selected by the European Commission as a flagship project in materials science and applications. The project comprises a large multidisciplinary consortium of 43 European research groups and companies and has the potential to make Europe a world-leader in this strategically important area of materials physics over the next five years.

The key scientific objective of the project is to develop new knowledge about the relationship between processing, structure and properties of intermetallic alloys. These special crystalline alloys are considered to be the materials of the future, with many different applications ranging from aerospace components to power generation systems.

Titanium aluminides, for example, have remarkable mechanical and physical properties at temperatures up to 800°C. It is the combination of high melting point, high strength and low density that make them ideal for high-performance gas turbine blades. These blades, which are produced by advanced casting techniques, will be used in the next-generation of turbines for modern power stations and aero-engines (figure 5.17).

Using titanium aluminide would result in a 50% weight reduction of turbine components. Such a significant weight reduction could ultimately lead to improved thrust-to-weight ratios of aero-engines, higher efficiency, reduced fuel consumption and lower exhaust emissions.

Intermetallic alloys are equally important in the field of advanced catalytic powders. Catalysts work by speeding up chemical reactions, thereby saving considerable time and energy. There are many industrial uses of catalysts, for instance, in the pharmaceutical, food and energy industries. In IMPRESS, scientists will investigate catalytic powders made from nickel and cobalt aluminides.

One of the gratifying aspects of IMPRESS is the fact that industry has been energetically involved from the outset and has defined the measurable targets of the project. These companies will now have direct exposure to the new knowledge and will be first in line for licensing and patenting.

The ISS, as well as other microgravity platforms, will be used extensively to perform benchmark experiments on these advanced intermetallic alloys. The unique data from these microgravity experiments will make a vital contribution to the project, by generat-

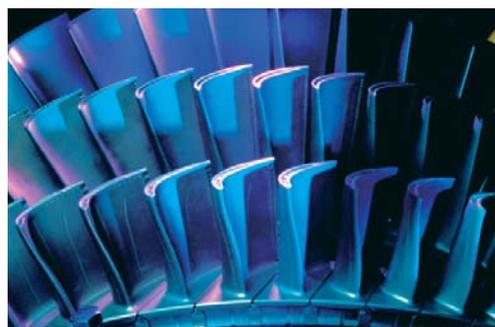


Figure 5.17: Cast turbine blades for use in gas turbines and aero-engines

Source: ESA

ing fresh knowledge, confirming theories, validating computer models and optimising industrial processes.

The various ISS facilities which are (or will be) used by the IMPRESS team include:

- the Electromagnetic Levitator (EML), which allows containerless melt processing and non-contact measurement of thermophysical properties;
- the Materials Science Laboratory (MSL), which permits solidification experiments of high-temperature intermetallic alloy samples;
- the IMPACT facility, which permits well-defined experiments in the field of nano-particle formation and agglomeration.

Chapter 6: Life sciences

6.1. Human and animal physiology

From genes to function in health and disease

6.1.1. Introduction and description

The purpose of the programme is to determine the effects of gravity on animal and human physiological systems from the level of the genes to integrated systems. To understand how gravity affects physiology is fundamental for our knowledge of how animals and humans have evolved on Earth and how gravity modulates mechanisms in health and disease. To obtain this goal, experimenters must have access to acute and long-term changes in gravity levels including 0g (microgravity). Therefore, spaceflight is an essential part of the programme.

There are many similarities between effects of low levels of gravity and those of ageing, diseases, and sedentary life styles. Therefore, research in microgravity adds to our knowledge of how to treat these conditions. Furthermore, research under 0g conditions contributes to the understanding of how gravity burdens the life of diseased individuals such as those with, for example, heart failure, osteoporosis, paralysis, etc. Therefore, physiological research in space is expected to lead to new knowledge, which will have the potential of improving treatment and rehabilitation and result in improved health for the general public.

6.1.2 Physiology report 2000-04

6.1.2.1. Cardiopulmonary physiology and fluid volume research in space

The classic hypothesis as to how the human cardiopulmonary system and renal control of fluid and electrolyte balance adapt to weightlessness has been challenged by data from space. Originally it was hypothesised that weightlessness would induce central blood volume expansion, which would lead to an augmented renal output of electrolytes and fluid. In the 1990s it was confirmed that central blood volume is increased by weightlessness, because the heart becomes distended. However, the mechanisms for this are surprising, because the increase in central blood volume is accomplished not only by the abolition of hydrostatic pressure gradients in the circula-

tion but also by a decrease in interpleural pressure.

Even though the heart and central vessels are distended in space, an augmented renal output of fluid and electrolytes has not been documented (Drummer et al. 2001; Nask et al. 2000). This has led to the hypothesis that sodium might be stored in interstitial tissues, which is a new concept in human physiology (Heer et al. 2000), and which has led to the development of new experimental models on the ground. If this new hypothesis is confirmed, its implications are potentially very important for understanding why some people develop hypertension.

Data from space have also led to the discovery that gravity affects the cardiovascular system in the front to back direction and vice versa in horizontal humans. Rohdin et al. (2003) observed that humans in the prone position during hypergravity oxygenated the blood more efficiently than supine humans. The implications of this discovery have a bearing on how to position patients with cardiovascular disease.

• *Prolonged spaceflight: A test-bed for understanding the effects of gravity on cardiopulmonary diseases?*

The new concept that gravity-induced mechanical pressure on body tissues in supine humans has a pronounced effect on the lung-heart interaction is of relevance for understanding the mechanisms of heart disease. In patients with heart failure, fluid and electrolytes are accumulated in the body, because the heart cannot supply the organs with blood as efficiently as in healthy people. The accumulation of fluid leads to oedema and further deterioration of the condition. A vicious circle is thus established. Furthermore, heart failure patients can experience difficulties when being supine. This syndrome might be partly caused by the gravity-induced pressure on the heart. Thus, the transverse gravitational stress in supine heart patients might explain some of the disease patterns. When a patient is upright, the weak heart has difficulties in maintaining blood pressure to the brain. Therefore, gravity is a burden for heart failure patients, both when supine and upright.

Heart failure patients also exhibit high levels of sympathetic nervous activity and of fluid and sodium retaining hormones. Astronauts in space exhibit the same patterns. The mechanisms of these augmented

hormone releases and of sympathetic nervous activity are different when comparing heart failure patients with weightless astronauts because the astronauts are still healthy. On the other hand, the activated hormone secretions and nervous activity might be caused by a diminished blood supply to the arteries: in the heart patients, because the heart is weak, and in astronauts in space, because blood volume is decreased. Therefore, prolonged spaceflight might constitute a test-bed for investigating aspects of the mechanisms of heart disease.

By comparing cardiovascular, hormonal and kidney variables of (1) healthy astronauts on the ground, (2) astronauts in space, and (3) heart failure patients, the following question can be addressed: How can astronauts during prolonged spaceflight exhibit the same physiological patterns as heart failure patients without being sick? An answer to this question might reveal new disease mechanisms of importance for treatment.

6.1.2.2. Bone

• Changes in biomarkers of bone turnover in microgravity

Microgravity leads to a very rapid bone loss of up to 1.4 % per month in the hip or 1.1 % in femoral neck (LeBlanc et al. 2000). This is about ten times higher than bone loss in postmenopausal women. Mostly, the in 1g environment, mechanically loaded bones suffer from bone mineral loss and very likely bone structure loss leading finally to disuse osteoporosis. Supporting the data from mechanically loaded bones, astronauts' bone mineral content of the distal radius – a non-mechanically loaded bone – show no change in space missions (LeBlanc et al. 2000; Vico et al. 2000).

In contrast to postmenopausal osteoporosis, where bone loss is mainly due to oestrogen deficiency, space flight induces bone loss by different mechanism than postmenopausal osteoporosis, namely, by decoupling of bone formation and resorption processes. In other words unloading of bone increases bone resorption while bone formation remains unchanged or slightly decreases. This was consistently shown in several space missions where biochemical markers of bone formation and resorption were analysed (Caillot-Augusseau et al. 2000) and is also supported by histomorphometric measurements of bones from rats after space missions (Vico et al. 1998). All these studies demonstrate that microgravity-induced uncoupling of bone resorption and formation occurs early after the loss of gravity.

However, comparable to the pattern of bone loss in microgravity – although of less magnitude – is the bone loss in any bedridden patient as shown in a couple of bed rest studies and in a sedentary lifestyle in both young and old people. A metabolic balance bed rest study by Baecker et al. (2003) even demonstrated that as little as one to two days of bed rest is sufficient to exacerbate bone loss. These data on bone formation markers and bone resorption markers in short-term bed rest studies also support the pattern of uncoupling of bone collagen synthesis and breakdown as in space flight and which has also been shown after long-term bed rest (Caillot-Augusseau et al. 2000; Zerwekh et al. 1998; Scheld et al. 2001; Vico et al. 1987).

Although mechanical loading is one of the most important measures to counteract muscle and bone loss in microgravity the optimal exercise regime is still lacking. Actually, astronauts have to train two hours a day with different training regimes but still lose bone and muscle mass. Development of more effective and more efficient exercise countermeasures that should lead to a full compensation of the sarcopenia and osteopenia in space is therefore mandatory. However, for an efficient training regime to keep up bone and muscle mass other prerequisites have also to be fulfilled which may affect bone formation and resorption processes, such as adequate nutrient supplementation. From all the missions it is obvious that the individual energy intake level seems to be too low, calcium and vitamin D supply seem to be inadequate, sodium consumption is too high, etc. In addition to these factors, a low-grade metabolic acidosis is shown (Smith 1997) which exacerbates the bone loss induced by mechanical unloading. As a result, further studies are mandatory to develop combined regimes to counteract bone and muscle loss in microgravity like new, less time-consuming, exercise regimes plus certain nutritional countermeasures.

Similar patterns of the bone formation and resorption markers as in microgravity or bed rest are shown in a sedentary lifestyle. Meanwhile there are case studies showing that even young people suffer from osteopenia because of their sedentary lifestyle. This leads to an increased risk of sarcopenia, osteopenia and osteoporosis especially in the Western world. Any countermeasure developed for the health of the musculoskeletal system during microgravity is therefore also highly applicable to people on Earth.

• **Prolonged spaceflight: A test-bed for understanding effects of disuse osteoporosis and development of countermeasures?**

It seems that the magnitude of bone loss in microgravity especially in mechanically loaded bone such as tibia and calcaneus is much higher compared to bed rest. Together with that the immobilisation-induced bone loss is reversible in most of the astronauts when mechanical loading was regained, i.e. when the astronauts come back to Earth. Although the time constant to regain bone mass is at least twice the period in microgravity, applied regimes seem to counteract bone loss at least partly. Space missions therefore are an ideal test-bed for the development of countermeasures. This is certainly valid for any bone and muscle loss induced by immobilisation. Even for postmenopausal women and/or ageing people (female and male) where the cause of bone loss might be different from disuse, these countermeasures would be of high value.

6.1.2.3. Neuroscience

Perhaps the most remarkable aspect of human exposure to weightlessness is the relatively limited impact on balance, locomotion and control of movement. In space-related neuroscience research, results indicate that the most obvious adverse consequence is space motion sickness, an unanticipated condition with a duration of typically less than two days. This phenomenon – along with another unanticipated condition called *mal de débarquement* that occurs during re-entry and after landing – is collectively called the “space adaptation syndrome”. Because of their interrelationship with space motion sickness, much emphasis has been placed on vestibular and oculomotor functions. However, vestibular changes during short-term exposure to weightlessness are relatively subtle. Thresholds for angular acceleration change little if at all and linear acceleration thresholds are inconsistently modified. The gain of the peripheral canal response is not affected during exposures of days or several weeks. Saccadic eye movements appear to be unaffected in weightlessness; however, eye movement in response to a visual stimulus, particularly in the vertical plane, can be greatly disrupted.

It is difficult to directly measure changes in the otolith organs, which are part of the balance system in the inner ear. Recent Spacelab experiments conducted in rodents indicate that the otolith crystals manifested no deleterious effects. However, there was a twelve-fold increase in the number of synapses in the hair cells in the maculae of the flight

animals as compared to the ground controls. A study recording the vestibular nerve impulse data from oyster toadfish flown on the Neurolab mission showed a decrease in resting activity of the nerve connecting the otolith organ to the brain.

Predictably, otolith-induced responses are especially affected by weightlessness; spinal and H-reflexes, vertical vestibulo-ocular reflex, and ocular counter-rolling are attenuated. The absence of gravity also modifies the stimuli associated with proprioception and impacts spatial orientation, including knowledge of position in the passive limb, difficulty of pointing accurately at targets during voluntary limb movement, modification of tactile sensitivity, and changes in the perception of mass. Results of pointing experiments are ambiguous because remembered target positions with the eyes closed are suggestive of either degradation in proprioceptive function, or an inaccurate external spatial map, or both.

Balance-control performance has been systematically tested before and after flight using posturography systems widely employed for the evaluation of balance disorders on Earth. Post-flight measurements revealed that some astronauts had clinically abnormal scores, being below the normative population fifth percentile. Post-flight re-adaptation takes place in about eight days after short-duration flights. The effects of demographic factors such as age, gender and longer mission duration on these responses need to be further investigated.

Typically, locomotion in weightlessness poses no problem and is quickly learned. However, adaptation continues for about a month. When moving about in space, the astronauts stop using their legs. Instead they use their arms or fingers to push or pull themselves. Consequently, new sensory-motor strategies emerge in weightlessness. Some of this newly developed sensory-motor programme “carries over” to the post-flight period, which leads to postural and gait instabilities and sudden loss of orientation in unstructured visual environments. In addition, disorienting illusions of self and surrounding environment motion occur during head movement induced by locomotion. Terrestrial patterns of anticipatory compensations are seen in-flight, although they are functionally unnecessary. Alterations in muscle structure and in motoneuron properties also occur during longer duration missions

Astronauts working in space must rely much more on vision to maintain their spatial orientation, since otolith signals no longer signal the direction of “down”. It has long been known that moving visual

scenes can produce compelling illusions of self-motion. These visually-induced illusions become even stronger in space since visual cues are unhindered by constraints from the otoliths which, in weightlessness, do not confirm or deny body tilt. However, some subjects are more “body oriented” and align their exocentric vertical to be along their longitudinal body axis, and perceive the body axis relative to placement.

These patterns point to alterations in the central nervous system rather than peripheral vestibular processing. However, there is still debate regarding a possible reinterpretation of otolith cues signalling translation rather than tilt after adaptation to weightlessness. It is known that vertebrate brains form and maintain multiple neural maps of the spatial environment that provide distinctive, topographical representations of different sensory and motor systems. Research indicates that multisensory space maps exist in the mammalian hippocampus, which has the important function of providing short-term memory of an animal’s location. The space maps in concert with memory are used in the navigation process, allowing the animal to recognise a previous location and move to a desired site. It was recently shown that this map system also contains information regarding head location in the gravitational field. A reorganisation of these spatial maps possibly accounts for the disorientation episodes in astronauts and the differences manifested from individual to individual.

Other arguments in favour of the role of spatial maps in the adaptation of sensory-motor functions to space flight arise from the results of space experiments on cognitive processes. For example, mental rotation of 3-D objects is apparently influenced by the presence of gravity. Several experiments demonstrated that the average rotation time per degree was shorter in-flight than on the ground. Both vertical and horizontal axes of symmetry were equally faster to identify in space, whereas a vertical axis of symmetry is typically easier to recognise on Earth than is a horizontal axis. Crew members frequently report difficulties evaluating time periods while in space. The absence of a gravitational reference system, which determines the vertical direction on Earth, also has an apparent influence on the mental representation of the vertical dimension of objects and volumes.

In summary, results from studies of human orientation and movement control in weightless conditions, including sensory functions, eye and body movements, and higher-level cognitive changes, show that when astronauts and cosmonauts return from extended space flight both their physical “plant”

and neural “controller” are structurally and functionally altered. There are clear distinctions between the virtually immediate adaptive compensations to weightlessness and those that require longer periods of time to adapt. However, little is known today about the adaptation of sensory-motor functions to long-duration space missions in weightlessness and to the transitions between various reduced gravitational levels, such as on the Moon and Mars.

The following examples of some very few selected scientific publications are an indication as to how the space physiology programme has developed within the past four years: Clement 2003; Drummer et al. 2001; Norsk et al. 2000; Heer et al. 2000; Rohdin et al. 2003; Vico et al. 2000.

6.2. Biology

6.2.1. Definition and scope of gravity biology

Scientists working in space and gravitation biology are investigating the responses of single cells and organisms to gravity, the only persistent factor during the evolution of life. While in the past the emphasis was mainly on the description of effects of gravity on biological systems, current research lines are increasingly directed towards understanding the underlying mechanism(s) controlling these responses. To achieve this objective, experiments from the genetic to the organismic level will be performed. The outlined transition has and will give deeper insights on the nature of interactions between cells and organisms with external factors in a very general sense.

6.2.2. Connections to other fields

6.2.2.1. Biology and physical science

In the most general sense the interaction of biological systems with the environment as well as intercellular processes always include physical parameters. Physics and chemistry provide the methodology and the theoretical background for understanding the behaviour of molecules and thus it is indispensable for the thorough understanding of biological systems. This becomes most obvious when a factor such as gravity, which is taken for granted in most cases, is absent. A simple example is convection which is necessary for water transport in plants. If gravity is absent, plants die with all the symptoms of drought even when a sufficient water supply is available if no appropriate countermeasures are taken.

In a more specific sense a strong connection to

physical science exists in the understanding of self-organisation of prebiotic and biotic systems. This refers to the origin and evolution of life in the presence and absence of gravity.

6.2.2.2. Biology and life science research

Obviously, strong connections exist between biology, exobiology and human and animal physiology. Biological research plays a major role in the search for life signs on other planets as well as in any project related to the origin and evolution in life. Some groups in biology deal with the description and understanding of life under extreme conditions (very low and very high temperatures, high and low pressures). Several projects (for example, EXPOSE) are planned or are already carried out. In addition, biology provides the basis of bio-regenerative life support systems. These systems will include photosynthetic organisms, and a clear understanding of the effects of the absence of gravity as well as long-term exposure to cosmic radiation is indispensable. Molecular and cell biology as well as developmental biology as two of the three scientific cornerstones in this field intend to supply functional explanations of biological processes at every level of complexity, and therefore, a basis for the understanding of processes in human and animal physiology. This includes the cellular and molecular analysis of phenomena like loss of bone structure and muscle mass which can be effectively studied in animal and/or cell model systems.

6.2.3. Biology report 2000-04

In the following a few examples for the development and the achievements in the different biology fields are given which are directly related to space experiments. The list is by no means exhaustive.

6.2.3.1. Molecular and cell biology

So far, experiments in microgravity have revealed that cellular systems sense the absence of gravity and that many functions in humans, such as bone development, heart function and immunocompetence are altered. Although the end result of these microgravity effects is not yet known it has been suggested that one reason might be the direct effect of gravity at the cellular level, and one hypothesis proposes an increase of programmed cell death (apoptosis) in microgravity. Recent studies in microgravity and hypergravity concentrated on the cytoskeleton and signal transduction chains, as they control fundamental cellular functions, such as maintenance of cell architecture, cell motility, cell division, regulation of

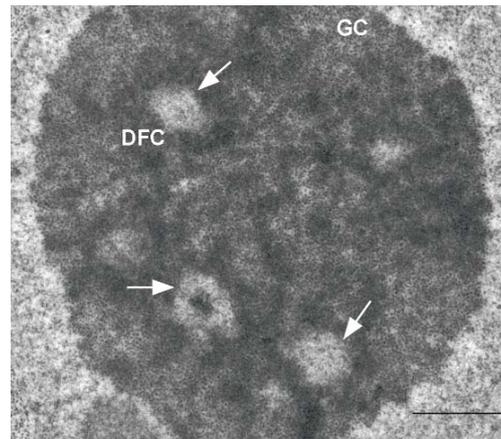


Figure 6.1: Nucleolus of an *Arabidopsis* root meristematic cell, grown in microgravity (STS-84 Mission), observed at the electron microscope. The nucleolar structure and nucleolar proteins are excellent sensors for alterations induced by the absence of gravity in signal transduction pathways related to cell proliferation.

Courtesy of F.J. Medina, CIB-CSIC, Madrid, Spain and J.Z. Kiss, Miami University, Ohio, USA

enzymes, ion channels and gene expression. Going beyond pure description of the phenomena to an understanding of the microgravity-induced alterations on the molecular and cellular level, increase our knowledge in basic science. This aspect has potential importance for human health considerations; for example, depression of the immune system or the induction of cancer which may become serious health issues on long-term space flights (figure 6.1).

6.2.3.2. Plant biology

The flowering plant *Arabidopsis thaliana* is a unique model that is used to elucidate the molecular mechanisms of gravity perception and transduction in higher plants. This model system allows the identification of the genes controlling gravity responses and the determination of their function. The many genetic and molecular tools for analysis of molecular processes make this very small organism ideal for research on the ground and in space.

In the last couple of years, major advances in understanding gravity signalling of *Arabidopsis thaliana* have been achieved. Finally, after many decades, a hypothesis for gravitropism of the root was verified and the molecular basis elucidated. Some of the major players in gravity signalling were identified and information on gene networks affected by gravity on Earth and in space using gene chips covering the full genome of this plant was obtained. These data provide now the basis for detailed cellular analyses of gravisensory/ mechanosensory processes (figure 6.2).

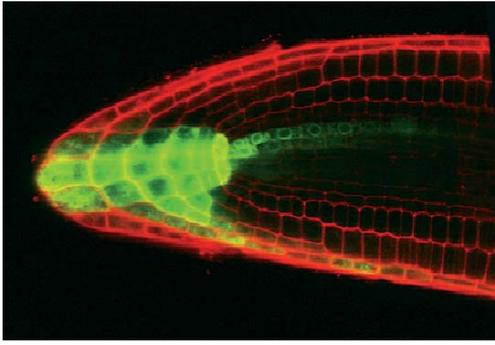


Figure 6.2: *Arabidopsis* root tip. Green colour indicates the presence of a plant hormone, auxin which is required for gravitropism

Courtesy of K. Palme, University of Freiburg, Germany

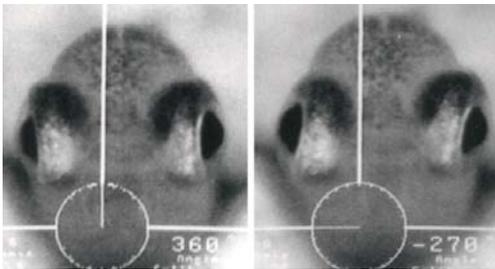


Figure 6.3: The picture shows the vestibulo-ocular reflex of a young fish during stimulation of its gravity sense organ by a lateral roll (right) compared to absence of stimulation (left). Note the asymmetrical posture of the eyes during stimulation

Courtesy of E. Horn, University of Ulm, Germany

6.2.3.3. Developmental biology

Current developmental biology faces a paradox: While cells clearly react to the absence of gravity by modifying their cytoskeleton and signal transduction pathways, the overall development seems to be ultimately unaffected. A better understanding of the developmental regulation mechanisms will reconcile these apparently contradictory results. In this respect it is important to proceed with long-term experiments (the ISS may enable this) that were not possible in the past. It could be that there are still effects that cannot be perceived in short-term experiments but become apparent in long-term experiments. In this sense it is necessary to improve understanding of how the phenotype is actually produced from the instructions stored in the genotype, and the nature of the actual mechanisms involved, as well as to understand how much physical and other external forces and processes contribute to the shaping of particular organisms. These data are critical for the evaluation of the possible outcome of extraterrestrial colonisation attempts. They are also critical for our scientific capability of giving answers to most problems in our ground base, the Earth.

Periods of life, revealing an extremely high sensitivity to altered environmental conditions, characterise the development of sensory, neuronal and behavioural functions. They are called “critical periods”. Space experiments involving fish and amphibians revealed critical periods for the development of the vestibular system. During space flights (Shuttle; Soyuz/ISS), a typical response called the vestibulo-ocular reflex which is induced by stimulation of the gravity sense organs (Figure 6.3) was significantly modified in an age-related manner by gravity deprivation. Most prominent was the observation that the vestibular system became more sensitive during the space flights, a feature which is in line with observations on gravity perception in astronauts.

6.2.4. Review of achievements after the Bischenberg workshop

The recommendations of the of the 2000 Workshop on ESA's Future Programme in Life and Physical Sciences in Space (ESSC-ESF 2001), held in Bischenberg, near Strasbourg, France identified several issues to be addressed in the near and mid-term future.

Concerns about potential shortcomings in reaching the best groups working in a given field of biology were discussed in Bishenberg. In this respect, great efforts were made by ESA to improve the peer review process for selecting experiments. At the moment, the selection process is considered by the biology group as one of the best organised in the whole of Europe. The announcements of opportunities (AOs) are available and accessible for everybody interested. Consequently, many new groups have entered the field. Nevertheless, certain suggested strategies should be more rigorously exploited. The representation of ESA in non-space meetings is still very limited. However, this also includes a higher visibility of the appearances of scientists involved in space experiments in meetings. Ground-based research is still not funded as recommended, thus reducing the interest of new groups in space biology. This limitation also applies to groups already involved in space research and impairs activities severely. Another unsolved issue is the attraction of young scientists and students to the field. The suggested grant programme for scientists and a space biology-related PhD programme are not implemented because of financial restrictions. Tough levels of competition for academic and institutional permanent jobs does not help young scientist involved in biological research in space, a slow-growing and still unappreciated field. Public outreach in terms of a

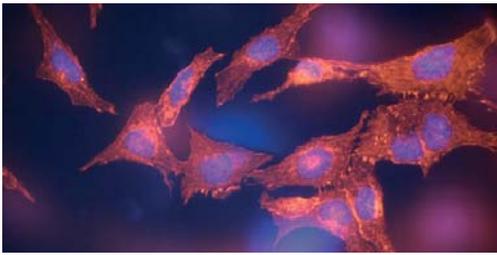


Figure 6.4: Osteoblast-like cells (mouse) grown on beads: Actin stained with rhodamine-phalloidin, DNA with DAPI
Courtesy of C. Baumstark-Khan, DLR, Cologne, Germany

quick dissemination of the results is another area where improvements are possible (figure 6.4).

6.2.5. Suggestions for ESA's future activities in biology

The biology group highly appreciates the current ESA bottom-up approach, namely that the definition of specific activities in space biology is guided by the applicant scientists. This will leave ample room for fast responses and flexibility, which is necessary in a very rapidly moving science such as biology. However, as stated in one of the general recommendations above, it seems reasonable to identify model systems where the combined efforts of several to many cooperating groups will drive the insights and understanding much faster and more effectively than spreading the expertise and resources among too many models. Focusing on shared and/or combined experiments on a limited number of model systems seems reasonable especially in the light of the current limitations in access to the ISS.

In the near future, while the focus will be on understanding the molecular basis of gravisensing and graviresponse mechanisms, the programme should extend to ecological and evolutionary aspects of the gravisensory apparatus. In addition, the ISS makes the analysis of long-term effects of microgravity on single cells, plants and animals possible for the first time. This field of research provides the knowledge necessary for the development of bioregenerative life support systems (figures 6.5 to 6.7).

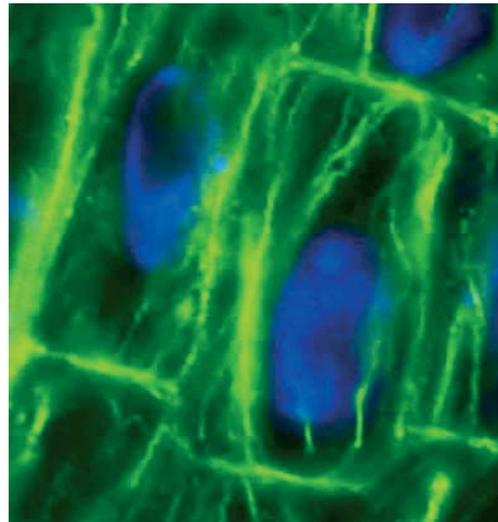


Figure 6.5: Maize root cells. Actin filaments seen in green, nucleus in blue
Courtesy of D. Volkmann, Uni. Bonn, Germany



Figure 6.6: How gravity shapes life morphology?
Courtesy of D. Volkmann, University of Bonn, Germany

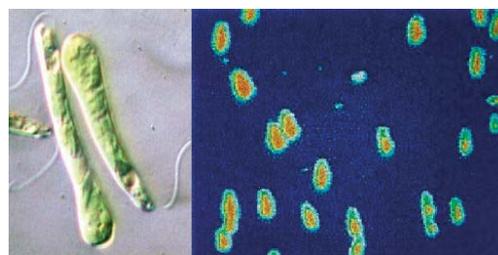


Figure 6.7: *Euglena gracilis* (left, light microscopy) and *Paramecium biaurelia* (right) (computer-controlled image analysis), typical examples for unicellular gravisensing organisms

Courtesy of D.-P. Häder, University of Erlangen, Germany and R. Hemmersbach, DLR, Cologne, Germany

6.3. Exobiology

6.3.1. Definition and scope of exobiology/astrobiology

Exobiology – or astrobiology – attempts to reveal the origin, evolution and distribution of life on Earth and throughout the universe in the context of cosmic evolution. In this attempt, we understand life as a system which is capable of demonstrating evolution by means of natural selection. The final goal is building the foundations for the construction and testing of meaningful axioms to support a theory of life. To reach this goal, a multidisciplinary approach is required involving disciplines such as astronomy, planetary research, geology, palaeontology, chemistry, biology and others. This field of exobiology research is reflected in the Cornerstone *Origin, evolution and distribution of life* of the ELIPS programme.

6.3.2. Review of exobiology achievements within ESA's programmes

The recommendations of the 2000 Workshop on ESA's Future Programme in Life and Physical Sciences in Space (ESSC-ESF 2001), identified the following three topics as research goals and questions to be addressed within the field of exobiology, the subjects of which are interlinked: (1) exobiology packages for exploration science missions with the targets Mars, Europa, comets, other solar system bodies and extrasolar planets; (2) chemistry of the origin of life; and (3) biological evolution of life. The following steps have been taken by ESA in due consideration of these recommendations.

6.3.2.1. Exobiology packages for exploration science missions

Within the programmes of ESA several space missions are in progress that have key objectives concerning the nature of extraterrestrial organic chemistry and the search for traces of past or present life on other bodies of the solar system. These include Mars Express (to Mars), Cassini-Huygens (to Saturn and Titan), and Rosetta (to the comet Churyumov-Gerasimenko). Concerning the search for life on Mars, orbiters, such as Mars Express will provide data on the geology (paleolakes, volcanism, hydrothermal vents, aqueous precipitates), climate (hydrosphere, duration of phases which allow liquid water) and radiation environment required for assessing its past and present habitability. The search for possible biological oases will be connected with the detection of areas where liquid water still exists. In

this connection, the finding of methane in the atmosphere of Mars by Mars Express is intriguing.

In addition to the exobiology packages, an experiment flown on a Foton re-entry vehicle, The STONE-1 experiment, was designed to test whether Martian sedimentary material could survive terrestrial atmospheric entry. A basalt, a sedimentary dolomite and artificial Martian regolith, were embedded into the ablative heat shield of the recoverable capsule of the Foton-12 spaceflight mission. The recovered samples have been analysed for their chemistry, mineralogy and isotopic compositions. Modifications due to atmospheric infall were tested by reference to the untreated samples. The dolomite sample was retrieved intact, although reduced to a depth of about 30% of its original thickness, suggesting that some Martian sediments could, in part, survive terrestrial atmospheric entry. A significant degree of isotopic exchange between silica and atmospheric oxygen during re-entry has been identified (Brack and Kurat 2000; Brack et al. 2002a, b).

ESA has initiated an exobiology approach to the exploration of the solar system by coordinating the study "Exobiology in the solar system and the search for life on Mars" (ESA 1999) which among others resulted in the recommendation of a suitable lander/rover package which includes subsurface drilling capabilities to search for signatures of life on Mars. This instrument package is the core of the Pasteur payload for the rover of the ExoMars mission planned for 2009. After a call for idea proposals by ESA, 22 out of 50 proposals were selected and the chosen teams are currently optimising the payload to serve the three objectives (search for past life, search for present life, and hazards to humans). For 2011, a Mars sample return mission is planned. The critical health issues in connection with human missions to Mars have been assessed in the HUMEX study by ESA (ESA 2003).

In order to learn more about the survivability and adaptive strategies of candidate microorganisms under Martian conditions, which is considered a prerequisite for search-for-life studies, the Topical Team, Responses of Organisms to Martian Environment (ROME) was set-up by ESA in 2003 and a laboratory programme on complex organic chemistry in a Mars simulation chamber has begun. Concerning planetary surface missions, ESA has established a planetary protection working group, is organising planetary protection courses, and has started an active planetary protection programme. The Cassini-Huygens mission has been enormously successful with the European lander Huygens providing impor-

tant data on the structure and composition of the atmosphere of Titan during descent, as well as on the geology and geomorphology of the surface of the planet.

Jupiter's moon Europa was recommended as a primary target for future exploration. This recommendation is based on the interpretation that Europa has a deep ocean below a thick crust of ice. More needs to be known about the composition, temperature of the ocean, about possible energy sources, and the ice crust/liquid/ocean floor interfaces, in order to assess the habitability of this moon. Since the detection and intense exploration of a deep sea biosphere on Earth and the detection of lakes under Antarctic ice, terrestrial analogues of a putative European submarine biota are available. So far, no missions to Europa are planned within ESA's programme.

6.3.2.2. Chemistry of the origin of life

For exobiology studies in Earth orbit, ESA has developed two facilities to expose organic and biological specimens to the conditions of outer space and to study their responses after retrieval. These are the BIOPAN facility on board the Russian satellite Foton which stays for about two weeks in Earth orbit (Figure 6.8) and the EXPOSE facility to be mounted at an external platform of the International Space Station (Figure 6.9). BIOPAN will resume its flights in 2005 and EXPOSE is scheduled for launch in 2005 and again in 2007-8 and will stay for more than one year in space. Exposing samples to the specific environment of outer space allows research directed towards understanding prebiotic chemical evolution processes, such as interstellar organic chemistry, photochemical processing in space, emergence of prebiotic molecules in space, and the delivery of organics to a planet (figures 6.8 and 6.9).

6.3.2.3. Biological evolution of life

The facilities BIOPAN and EXPOSE also provide opportunities for studying the limits of life in extreme environments. By using optical filters, the biological effects of selected spectral regions of solar UV radiation can be studied. Questions to be tackled include the impact of UV radiation climate on Earth's earliest biosphere, the role of an ozone layer in the screening of biologically harmful UV radiation, the habitability of other planets, for example Mars, and the chances and limits of interplanetary transfer of life, and the protection of microorganisms by meteorites. The results obtained from such space experiments have supported the assumption of "lithopanspermia", namely that resistant microorganisms might with-

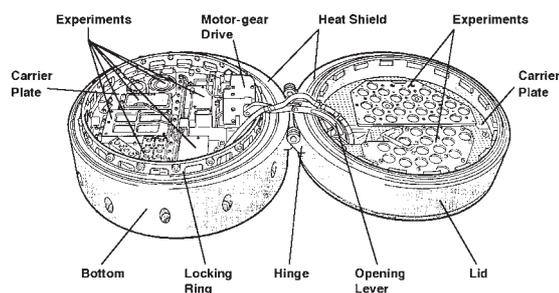


Figure 6.8: BIOPAN facility to be accommodated outside the Foton satellite

Source: ESA



Figure 6.9: EXPOSE facility to be attached to the ISS

Source: ESA

stand the severe strain in outer space thereby surviving, within meteorites, a hypothetical journey from one planet to another. Currently, the experiment requirements and test parameters are being verified during a set of experiment verification tests (EVTs).

6.3.2.4. Use of ground-based facilities

The participants of the 2000 ESF-ESSC Bischofshausen workshop further recommended that ESA should support ground-based work in mission preparation, laboratory testing, terrestrial analogues etc. A strong ground support programme would substantially support the realistic planning of future space experiments as well as search-for-life experiments. With the ground-based programmes SSIUOX (Space Simulation for Investigating Organics, Evolution and Exobiology) and Complex Organics on Mars, ESA has started to support ground-based studies in connection with exobiological research. Another interesting approach is the ESA Topical Team, Boundary of the Biosphere with the aim of designing experiments for

exploring the vertical profile and the upper boundary of the biosphere by use of rockets or balloons, sterile sampling devices, and modern molecular biology analysis. With regard to bioregenerative life support studies, the ESA-funded REGLISSE study defined European facilities suitable for preparative ground-based studies (<http://www.estec.esa.nl/ecls/melissa/attachments/REGLISSE>).

6.3.2.5. Outreach and education

Following recommendations from the 2000 ESSC-ESF workshop to establish a structure and budget for effective outreach and education activities, ESA has established the Virtual Institute of Exobiology at ESA/ESTEC (<http://www.spaceflight.esa.int/exobio>) thereby providing a platform for communication, training and education in the field of exobiology. This virtual institute also hosts the web page of the European Astrobiology Network Association (EANA) a network that currently links scientists active in exobiology from 17 European nations.

6.3.2.6. Internal structure of ESA

To maintain and manifest European competitiveness in this rapidly emerging field of exobiology, it was recommended that ESA strengthen its role as a cooperator and supporter of international collaboration in the field of exobiology. It was also felt that, as the programme is science driven, the ESA management structure needed to be changed and a scientific advisory structure for an interdisciplinary activity was required. Several steps have been taken by ESA in this direction, such as the preparatory phase of the Aurora programme with its Exploration Programme Advisory Committee.

6.3.3. Suggestions for ESA's future activities in exobiology

Considering the upcoming opportunities to explore the planets, moons and other bodies of our solar system by orbiters and robotic landing missions, as well as the perspectives of future human exploratory missions to the Moon and to Mars, the participants of the 2004 ESSC-ESF workshop recommend the following as main research goals to be addressed in exobiology:

- the detection of signatures of life on other planets or other bodies, and
- the provision of supporting information required to enable human exploratory missions.

These two goals are well covered by the two cornerstones of the discipline astrobiology and plane-

tary exploration of the ELIPS programme:

- *Origin evolution and distribution of life*, and
- *Preparation for human planetary exploration*.

The focal area of the cornerstone *Origin, evolution and distribution of life* is the search for extraterrestrial life which includes the understanding of:

- the conditions for the emergence of life:
 - astrophysical prerequisites for the habitability of planets based on geophysical modelling;
 - in situ analysis of planetary minerals, isotope fractionation and organics in meteorites, dust;
- the occurrence of traces of past and present life and its precursors:
 - chemistry applied to prebiotic chemistry: conditions and prerequisites for early synthesis of biomolecules, hydrophobic compartmentalisation, early biochemical pathways;
 - surface mediated catalysis on minerals, clays etc;
 - reliable indicators of life;
- the conditions for maintaining active life:
 - limits of life;
 - environmental, energetic and trophic determinants and limitations, minimum requirements for a functioning biological cell;
 - evolution of ecosystem complexity: ecological genomics and community systems biology.

The focal area of the cornerstone *Preparation for human planetary exploration* is the understanding of relevant health issues, above all radiation health, gravity-related effects, as well as psychological issues, to provide a safe and efficient exploratory mission scenario. Future human exploratory missions should be driven by scientific, technological, cultural and economic considerations which can only be accomplished in a global enterprise by the joint efforts of the various disciplines involved. Essential contributions from the discipline astrobiology and planetary exploration include items, such as the following:

- definition of the in situ scientific activities related to the search for signatures of life;
- the radiation field and its biological effects for radiation health issues;
- development of life support systems including bioregenerative approaches; and
- detection of microbial contamination, control and prevention including the assessment of genetic alterations in possibly pathogenic microorganisms.

These studies include preparatory robotic space missions, use of the ISS, as well as supportive ground-based studies.

6.3.3.1. Detection of signatures of life on other planets or other bodies

In order to design the right search-for-life experiments; for example for Mars surface missions, the exobiology group suggests that an understanding of the limits of life on Earth is a necessary prerequisite. This includes assessing the geological and environmental constraints and conditions on other planets/moons for supporting some kind of terrestrial life, identifying the variety of geochemical cycles serving as energy sources, and exploring life's strategies to adapt and respond to harsh and extremely variable conditions. This information will facilitate determining the "life window" for target planets and moons, as well as the design of tailored approaches for the detection of signatures of past or present life or its precursors on, for example, Mars.

• *Understanding the limits of life*

On Earth, organisms live in specific ecosystems, each corresponding to a specific set of geological and environmental conditions (atmosphere, hydrosphere, lithosphere). Until recently, all known ecosystems were mostly dependent on solar energy (photosynthesis driven). The recent finding of a huge biomass pool in deep sediments and rocks, whose regeneration is driven mainly by chemosynthetic microbial processes, has considerably increased the known terrestrial biomass. Whether this newly detected biomass is based on primordial reduced substances (energy sources), or the liberation of sun energy captured in the form of recalcitrant organics (kerogen?), or reduced metal and sulphur compounds, is not yet clear. The interactions of rocks, sediments and hydrosphere with the biota control the planetary atmosphere. Such a dynamic is necessary to maintain energetic non-equilibrium states, to allow recycling of chemicals which can serve as nutrients for growth, and to keep the biosphere within a range of physico-chemical conditions suitable for life. In contrast to the tectonic dynamics characteristic of Earth, Mars apparently has had stable conditions for billions of years which makes it less suitable for the support of life at the present time (it is the tectonic recycling of nutrients that supports life on Earth today).

Many geochemical cycles on Earth are influenced by microorganisms. They actively cycle the compounds which are energy and electron sources for assimilative and dissimilative branches of metabolism. Directing energy flow and recycling of mass maintains environmental conditions that sustain life. Examples which illustrate consequences of biological activities are the oxidative atmosphere, the ozone

shield, inorganic carbonate and organic fossil carbon deposits, banded iron formations, biogenic methane, and nitrogen fixation. The carbon, iron, sulphur and manganese cycle, and their control by microorganisms, need to be studied under extreme conditions similar to those which are expected on Mars and Europa. The sulphur and iron cycles are of special interest with regard to Mars, because reduced sulphur and iron compounds can serve as electron donors in oxidative metabolism, whereas not fully reduced sulphur compounds and ferric iron can serve as electron acceptors in reductive metabolism; both processes can be done by terrestrial microorganisms aerobically or anaerobically. A number of different compounds produced as a result of microbial metabolism can serve as indicators for life in life-detection experiments.

Microorganisms have invented several strategies to cope with and adapt to environments of a wide range of physical and chemical extremes and to be selected for living in them. Examples are microbial ecosystems in deep crystalline rock, inside rocks in cold and hot deserts, inside crystalline salts from evaporite deposits (Figure 6.10), as well in hot environments such as the black smokers in the deep ocean. There are two modes of adaptation, either short-term adaptation caused by certain changes in metabolisms, biosynthesis, and life activities in general (resting stages), or long-term adaptation based on genetic alterations (mutation and selection). Model systems for further studies on the responses of life forms towards extremes include the prokaryotic bacteria and archaea, simple uni- and multicellular organisms, dormant/resting forms, seeds, lichens and others. Environmental parameters of interest are low and high temperature, pressure, pH, ionising and UV radiation, chemicals (salinity, heavy metals), water availability, low or high gravity, lack of easily accessible nutrients and combinations of these factors. Interesting questions to be addressed are as follows:

- How do membrane lipids and enzymes respond to temperatures and pressures compatible with life?
- How could extremely slow metabolism be measured?
- How long can truly dormant cells survive?
- How could evolution over time in layers of geological samples (for example, permafrost) be detected?
- What limits genetic alterations and adaptation through selection (in measurable time scales)?
- How do different organisms respond to specific stress conditions? (figure 6.10)

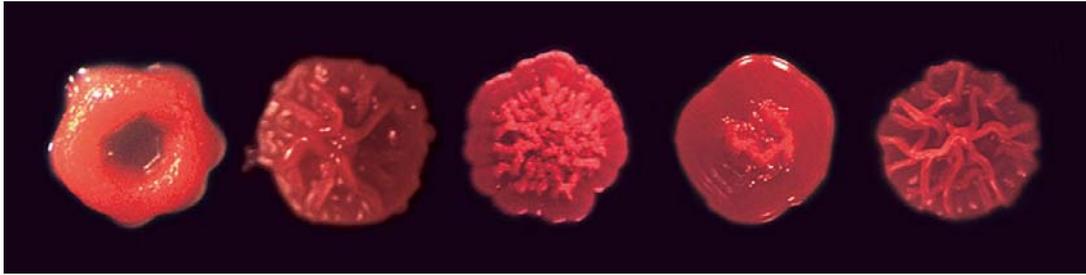


Figure 6.10: Colonies of pigmented halobacterial isolates from Alpine rock salt of Permian age. Diameter of colonies is approximately 1 cm

Courtesy: H. Stan-Lotter, Institut für Genetik u. Allgemeine Biologie, Universität Salzburg, Austria

Many microorganisms possess strategies for surviving in unfavourable conditions by converting into a kind of dormant state and are capable of regaining full metabolic activity once conditions become less hostile to life processes. Hence, the limits for microbial survival extend much further than those for growth (Table 6.1). Temporary transition of microbial cells to the dormant, so-called “anabiotic” state, which involves biochemical, physiological and ultra-structural changes, is a widespread mechanism developed by organisms to promote survival in temporary hostile conditions. More intriguingly, several multicellular organisms, such as animals, plants and fungi, are able to survive harsh conditions, for example, occasional drought, by entering a state of life suspension (= dormancy), and resuming activity when conditions become suitable again. During dormancy, any activity is suspended and metabolism stops, but both features are restored at the end of dormancy (Figure 6.11).

• Determining the “life window” for target planets and other bodies

Assuming the occurrence of liquid water as one of the prerequisites for habitability of a planet or moon, Mars and Jupiter’s moon Europa are prime candidates for further exobiology studies. There is ample evidence for ancient water on Mars: huge outflows, gullies, riverbeds, flooded craters and, more recently, images of water trickling down slopes in the recent past (~ 1000 years ago), as well as the detection of water by ground-penetrating radar by the orbiter Mars Express. Certainly there is still some water vapour in the thin atmosphere and there are considerable quantities of water in the form of ice at the polar caps. There may also be water in the form of permafrost just below the surface. Further down there may be even liquid water melted by geothermal heat. Extraterrestrial halite has been detected in SCN meteorites, which originate from Mars. Sites on Mars, where liquid water exists today, at least temporarily, might offer conditions favourable to life forms comparable to terrestrial microbial communities that inhabit permafrost, deep subsurface regions or evaporites. Dry interim periods might be survived by “Dauerforms”, comparable to bacterial spores, or

Table 6.1: Environmental limits for growth or survival of microorganisms and environmental conditions at the Martian surface

Parameter	Growth	Survival	Martian conditions
Temperature (°C)	-20 to +113	-262 to +121	-123 to +25
Pressure (Pa)	10^5 to 10^8	10^{-7} to $\geq 10^8$	560
Ionising radiation (Gy)	= 50	≤ 5000	= 0.2 ⁽¹⁾
UV radiation (nm)	terrestrial (≥ 290)	\approx terrestrial (≥ 290)	≥ 200
Water stress (α_w)	≥ 0.7	0 to 1.0	7×10^{-4} ⁽²⁾
Salinity	$\leq 30\%$	salt crystals	regional high (?)
pH	1 to 11	0 to 12.5	(?)
Nutrients	high metabolic versatility, high starvation tolerance	not required, better without	(?)
Gas composition	different requirements (oxic or anoxic)	better without oxygen	95.3% CO ₂ 2.7% N ₂ 0.13% O ₂
Time (a)	≤ 0.5 ⁽³⁾	$\leq (25 - 40) \times 10^6$	(?)

1: per year; 2: g/cm³; 3: generation time

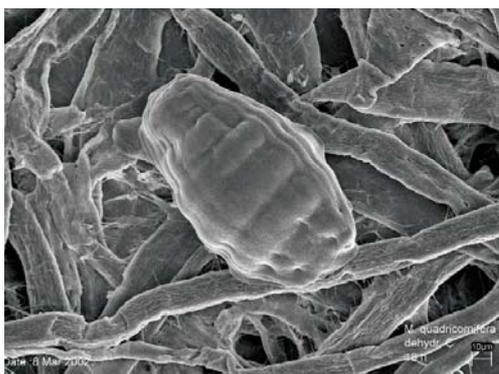


Figure 6.11. SEM image of an anhydrobiotic (dormant) bdelloid species (*Macrotrachela quadricornifera*) (scale bar = 26 μm)

Courtesy: C. Ricci, Department Of Biology, University of Milan, Italy

mummified cells, that are adapted to escape temporally and/or spatially from unfavourable conditions.

Europa represents an important exobiology target since it has been established with high probability that this moon of Jupiter harbours an ocean of liquid water beneath a thick ice crust. In addition to liquid water, carbon, energy sources and oxidants are needed to support life as we know it on Earth. If carbon was delivered by impacts of various bodies (although crustal resurfacing has eliminated any older impact craters), the question of energy sources is still open and potential terrestrial analogues have been pointed out. However, the existence of liquid water beneath the ice crust might be the result of deep hydrothermal activity, radioactive decay and/or tidal heating.

The other small bodies of the solar system, such as Saturn's moon Titan, comets and asteroids, are candidates for understanding prebiotic chemical evolution.

• ***Candidate signatures of life (precursors, present and past life)***

Atmospheric and hydrospheric chemistry which is far from thermodynamic equilibrium may, in the absence of an obvious energy source, be an indication of life. Since our understanding of the nature of life requires the presence of an information carrier which is capable of self-replication, functional and informational molecules such as proteins and nucleic acids are obvious biomarkers (including possible nucleic acid precursors). The problem becomes more complex when fragments of such molecules are encountered. In such cases homochirality provides a method of distinguishing between prebiotic and biogenic sources (although molecular homochiral-

ity is probably a sign of life, non-chiral systems are also theoretically possible). Since small organic molecules may also be regarded as candidates, one has to bear in mind that many organic compounds can also be generated in a prebiotic environment. Metabolites such as oxalic acids, polyfunctional acids and similar compounds are typical products of biological systems, but they can also be found in prebiotic conditions. Other molecular biomarkers are hopanes, hopanoids, steranes, or pigments. In such cases, an important signature would be the presence of isotopic fractionation. For example, typical biological isotopic fractionation patterns of C, S, or N, in the form of metabolic products such as organic carbon compounds, but also carbonates, sulphur and sulphur compounds, nitrogen oxides and ammonium compounds, could be indicative of active life processes. Table 6.2 lists candidate biomarkers and instruments to detect them.

Life forms can also be detected by their morphology, such as cellular structures (living and dead cells) or colonies which are multiplications and growth structures in a tissue-like context. Biofilms represent microbial communities where cells often produce large amounts of extracellular polymeric substances (EPS). These molecules have a tendency to polymerise, to serve as nucleation sites for precipitation and be mineralised, thus forming characteristic biosignatures.

Array-based technologies might be a direct approach for the detection of life on Mars. The technique allows the identification of biological molecules through their specific interaction with protein or nucleic acid complements. Consensus sequences of fungi and cyanobacteria, as well as bacteria, archaea and other biomarkers (hopanoids, triterpenoids, pigments, nitrogen compounds, collagen, keratin and conserved proteins) are putative scavengers. Appropriately devised arrays may be able to detect ancient and present life forms on Mars, provided that the appropriate components are present on the array chips.

Biostructures such as biominerals and biocorrosive patterns are indirect biosignatures. Several different organism-groups create erosive patterns: biopits, biochipping, or bioexfoliation on exposed rock surface which can be discriminated from physicochemical weathering. Many microorganisms produce a large number of minerals under physiological conditions and in places where they are not observed under normal thermodynamic conditions (for example, silica, iron precipitates, such as magnetite, jarosite, hydroxides, sulphides, apatite, forsterite,

oxalates). Sometimes the bioprecipitates can create macroscopic structures, such as stromatolites, corals, bioherms and limestones.

• **Space missions and supportive ground-based studies**

ESA should continue to have Mars as the prime target for exobiology research in the solar system and ExoMars should be the next step in this direction. The ongoing Mars Express mission will allow exploration of selected sites for the next Mars exploratory missions of ESA, such as ExoMars, using rovers with high autonomy and equipped with the analytical

capability to select suitable drilling sites or exposed vertical stratigraphy to find signs of extinct or extant life. This will require the development of an efficient Mars drilling system and the correspondent sample analysis suite to be used in the underground exploration of selected sites. In addition, the habitability of these regions should be explored by in situ measurements of the climate, radiation environment, and surface and subsurface chemistry in dry and wet state. Following missions should include a sample return of both surficial and drilled samples under conditions allowing putative organisms to survive the journey back to Earth.

Table 6.2. Biomarkers and modes of their detection

Morphology	Instrumentation	Space applications
1. Cell		camera
size	microscopy (light and other)	microscope (optical, AFM, confocal laser)
shape	microscopy (light and other)	
cell division	microscopy (light and other)	
cell complexity	microscopy (light and other)	
flexibility	microscopy (light and other)	
evidence for lysis	microscopy (light and other)	
characteristic structures	microscopy (light and other)	
cell wall structures	microscopy (light and other)	
EPS	microscopy (light and other)	
2. Colony		
multicellular and multispecies organisation	microscopy (light and other)	
EPS	microscopy (light and other)	
pleomorphism	microscopy (light and other)	
3. Biofilm		
Cells and inorganic particles embedded in an organic matrix	microscopy (light and other), plus EDX, probe, ToFSIMS, nanoSIMs	APX, Mössbauer, Raman
4. Biostructure		
stromatolites	observation, microscopy	CCD camera
biominerals	microscopy (light and other), plus EDX, probe, ToFSIMS, nanoSIMs	microscope, APX, Mössbauer, Raman, XRD
biodissolution	microscopy	CCD camera, AFM, algorithm chip
Biomolecules		
Proteins and nucleic acids and building blocks	GC-MS, HPLC, PCR, Raman, FTIR	biochips, HPLC, GC-MS, Raman, FTIR
Other biomolecules	GC-MS, HPLC, PCR, Raman, FTIR	biochips, HPLC, GC-MS, Raman, FTIR
Isotopes	MS, GC-MS	MS, GC-MS
Prebiotics		
small reactive molecules	GC-MS, derivatisation-HPLC	GC-MS, HPLC
chirality	HPLC, GC	
oligomers, polymers	HPLC, GC-MS	

Exploration of Europa's sub-ice ocean and its potential for habitability will be another important highlight in exobiology. A mission to Europa should include (after a precise mapping of the surface and search for a thin crust region) a landing package with the ability to penetrate as deep as possible into the ice and search for biosignatures of life. To be prepared for such a future exobiology exploration of Europa, ESA should initiate a study on the exobiology potential of Europa and ways to explore this.

Exploration of the planets and moons of our solar system that have the potential to harbour extraterrestrial life forms requires compliance with the Planetary Protection Guidelines as laid down by the Committee of Space Research (COSPAR). ESA should continue and intensify its activities in planetary protection, especially in the development of measures to prevent the transfer of Earth-born organisms and organic compounds to other planets and moons, by:

- developing and validating alternative sterilisation methods and designing “germ-free” assembly facilities compatible with delicate hardware;
- developing methods for qualitative and quantitative determination of culturable and especially non-culturable microorganisms;
- archiving the microorganisms isolated from spacecraft and spacecraft assembly facilities; and
- establishing internationally certified laboratories at the launch sites, equipped with state-of-the-art and fast microbial detection and identification instrumentation (for culturable and non-culturable microorganisms).

Furthermore, ESA should assure proper quarantine measures for samples returned from other planets and/or moons in order to prevent the contamination of terrestrial ecosystems, for example by establishing a certified Mars sample receiving laboratory. All planetary protection measures and results should be made publicly available.

A substantial part of exobiological research can also be done in Earth orbit; therefore ESA should continue to provide exposure facilities on the ISS and on autonomous free-flying satellites. Using defined and controlled space parameters, such as solar UV radiation (entire extraterrestrial spectrum, selected wavelength bands), cosmic radiation, vacuum (or defined atmospheres with different composition and pressures), and defined temperature ranges, exposure experiments will include studies on:

- the viability of multicellular and unicellular organisms; for example bacteria, archaea and bacterial

spores, microbial communities from extreme environments, other dormant organisms (for example bdelloid rotifers) or stages (resting eggs, seeds, cysts);

- the effect of protective agents, such as secondary metabolites (carotenoids, melanins, flavonoids, tocopherols), other molecules (for example, trehalose, saccharose, EPS), presence of a salt crust, or of rock varnish and soil layers;
- the attachment of microorganisms to material surfaces, for example, colonisation and establishment of biofilm-like growth; and
- the stability of prebiotic molecules in outer space conditions.

These experiments would require the following amendments to exposure facilities:

- a sun-pointing device to apply controlled periods of insolation, allowing accurate exposure of the samples in dose and spectral range; alternatively, this could be achieved by use of sun-pointing free flyers;
- temperature control, especially to keep samples at sub-zero temperature during sun-exposure.

In preparation for future exploratory missions, ESA should continue to support related laboratory studies using ground-based facilities. These should include the support of experiments using planetary and space simulation facilities allowing the simultaneous investigation of the effects of different parameters in defined combinations, such as UV-radiation, ionising radiation including heavy ions, vacuum or low pressure conditions, different atmospheric compositions, temperature, dust, diurnal profiles (for example on Mars).

These simulation studies will also elucidate potentially important pathways of prebiotic synthesis, especially selective processes which would be necessary to simplify reaction mixtures, specifically catalyse important pathways, and chirally enrich enantiomeric mixtures of asymmetric products. The study of potential precursors of the first RNA molecules and particularly of possible self-replication mechanisms, is also of central interest in the field. Additional studies include the isotopic fractionation ratios of model synthetic pathways, as well as the study of models of reaction mechanisms on interstellar dust grains, and the compilation and correlation of data on the occurrence of organic molecules in meteorites. Such studies, although possibly not contributing directly to specific flight experiments at any given time, are essential for the planning of future

exploratory missions, as well as for the interpretation of analytical results, and thereby, for the long-term goals of exobiological research.

In addition, ESA should consider supporting field studies in regions which are considered as terrestrial analogues of extraterrestrial habitats. Interesting model systems include deep subsurface rock laboratories, tunnels and caves with fully chemotrophic metabolic cycles, and key drill sites. This will allow the study of:

- metabolic cycles and the organisms that drive them (qualitative and quantitative); and
- energetics, namely, available energy sources and how much energy is dissipated during biomass formation, and how much of this primary biomass ends up as stored carbon or is recycled in short food chains.

Extreme environments will also allow the testing and validation of sensitive detection devices for signs of past and present life in preparation for life detection experiments on Mars and on Europa.

6.3.3.2. Preparatory studies supporting human exploratory missions

There are a multitude of reasons for a strong avocation of manned missions to Mars. Overall, the human brain, with its stored knowledge and experiences, together with its capacity for learning and decision-making, is extremely fast and efficient at analysing new or different situations and discriminating between normal and unusual phenomena. Preliminary exploration of Mars will have a strong geological component. This is one science in which long training and experience are fundamental to efficient and correct exploration/investigation, which cannot be replaced by robotic investigation. Further considerations include the fact that human missions are of even more interest to the public, who will be ever more willing to fund such enterprises.

Such future exploratory missions to the Moon and to Mars will add a new dimension to human space-flight, that concern the distance of travel, the radiation environment, gravity levels, the duration of the mission, and the level of confinement and isolation that the crews will be exposed to. Within the discipline Astrobiology and Planetary Exploration of the ELIPS programme of ESA, scientific support can be provided that is required to enable human health and efficiency on a mission, for example to Mars. This includes items such as:

- development of life support systems including bioregenerative approaches;

- early detection of microbial contamination, control and prevention, including the assessment of genetic alterations in possibly pathogenic microorganisms; and
- the radiation field, its biological effects for radiation health issues.

The studies will include preparatory robotic space missions, use of the ISS, as well as supportive ground-based studies. However, in order to enable safe and efficient human missions to Mars, additional contributions from the other disciplines of life sciences are required.

• Development of life support systems (LSS) including bioregenerative approaches.

Whenever human beings live and work in a confined habitat over extended periods of time, it is the task of the life support system to achieve and control a physiologically acceptable environment within the habitat. Efficient environmental control and life support systems (ECLSS) essentially takes charge of two complementary functions in a balanced and controlled manner: on one hand, it provides the input resources required for humans and other biological species to live and survive in this habitat, on the other hand it processes human and other wastes. Whereas the LSS on the ISS is based almost entirely on physico-chemical processes, exploratory missions demand alternative methods of ELSS, including biological/bioregenerative processes mimicking natural processes of our biosphere on Earth, and the use of natural resources available on extraterrestrial bodies. Bioregenerative life support systems (BLSS) use higher land plants, cyanobacteria and bacteria for a diversity of purposes as shown in Table 6.3. Current model systems are based on plants, on closed or semi-closed loops with microbial compartments (coupled with plants) or on algae and possibly animals (fish). Whereas higher plants can be used in several functions in a BLSS, one has to consider their high sensitivity to plant diseases and some chemicals; for example ethylene. Algae are very efficient in air revitalisation, however they need to be processed for use as food; they are also sensitive to virus or pathogen infections. Bacteria and cyanobacteria have been successfully tested within the European MELISSA project (<http://www.estec.esa.nl/ecls/default.html>). Further studies on BLSS are required to develop a reliable hybrid ELSS for human exploratory missions. Besides MELISSA currently developed by ESA, other recognised ECLSS include Bios 3 (Russia), CEEF (closed ecology experiment

Table 6.3. Functions of different biological systems in a bioregenerative life support system

Function	Higher plants	Cyanobacteria	Bacteria/Fungi/Yeasts
Oxygen production	+++	+++	±
Carbon dioxide uptake	+++	+++	±
Production of molecules essential for human beings	+++	+++	±
• vitamins	+++	+++	±
• amino acids	+++	+++	±
• fatty acids	+	–	±
• antioxidants using molecular engineering	+	+	±
Food production in general	+++	+	±
Waste management	±	–	+++
Water recycling	++	+	+++
Symbiosis with bacteria and fungi for optimising output	+	–	–
Air decontamination	+		+++
Psychology and emotional relief	+++		–
Enhancing perceived food quality	+++		–

facilities, Rokkasho, Japan) and BIOPLEX (NASA Johnston Space Center).

• *Microbial contamination, control and prevention*

Microorganisms colonise all types of material surfaces, both natural and human-made. Some of these materials are degradable, others not. Thus, degradable materials have two functions, to provide nutrients (substrate) and to provide a place for settlement/adhesion (substratum). Non-degradable materials provide only the place for adhesion (substratum). The latter may, however, be influenced and modified because of the microbial colonisation by, for example, excretion of coloured metabolites, excretion of organic solvents (polymers may be susceptible to these compounds), excretion of exoenzymes and/or emulsifying agents (detergents etc.). In addition, microorganisms might excrete malodorous compounds.

Whenever conditions for life are given, microorganisms will be present and start to metabolise whatever compound is present. Thus closed systems, such as space stations, spacecraft or planetary habitats, will have to deal with biofilms covering all types of material. These biofilms may cause serious problems by degrading susceptible compounds, including minerals, metals, polymers etc. Since absolute sterility is not possible, a balance has to be established between deleterious, negligible and wanted effects. For this purpose, the affinity of microbial biofilms to constructional materials needs to be evaluated and

appropriate countermeasures need to be developed.

Furthermore, effective contamination-control measures need to be developed in order to ensure proper hygienic conditions over long periods of human presence in space and on Mars. This includes regular measurements of the number of microorganisms in water, air, work areas, and living quarters, and the use of quick diagnostic tests for infectious diseases affecting humans and the identification of the sources of the pathogen(s). An efficient control of the biological stability and of alterations within the BLSS needs to be established.

• *Characterisation of the radiation field and its biological effects for radiation health issues*

The radiation field in space is drastically different from that on Earth: it consists of very energetic, heavy charged particles. Environmental doses are higher by a factor of 100 compared to the Earth surface, and in solar particle events (SPE) doses may reach lethal levels. All biological processes may be influenced by radiation. In view of human exploratory missions, it is important to note that radiation can cause cancer and is therefore a risk to humans, and that the astronauts can be seriously injured by the action of SPEs. Europe has gained a leading role in space radiation dosimetry in low Earth orbit and the development of measuring devices (for example, the human phantom Matroshka, installed outside the ISS), as well as in basic radiation biology with particular emphasis on the action of charged particles (for example, at GSI, GANIL, etc). This

knowledge offers the key for further studies on robotic precursor missions to assess the radiation risks during exploratory missions as well as on the ISS and to determine interactions of radiation and weightlessness on biological processes.

• ***Space missions and supportive ground-based studies***

Europe has gained a competitive status in several fields of life sciences, which are required to support human exploratory missions. This state of knowledge and experience provides a solid foundation for future involvement in international human exploratory missions. In order to sustain human health, wellbeing and efficiency on a long-term interplanetary mission, such as to Mars, various preparatory steps need to be taken which involve forthcoming space missions including the use of:

- robotic precursor missions orbiting Mars;
- robotic precursor missions landing on Mars; and
- the ISS or other human missions in low Earth orbit.

Furthermore, terrestrial test-beds and simulation facilities are required which include

- and bed-rest facilities; and heavy ion accelerators for radiation issues;
- isolation-confinement simulations, Antarctica, underwater, off-shore habitats,
- laboratory facilities and habitable closed chambers with ELSS.

More information is required on the environmental parameters during interplanetary transfer and at defined sites on Mars in order to provide baseline information for future activities in human exploration, in exobiology and for planetary protection considerations. Parameters of potential hazards to humans on Mars include the radiation environment, potentially toxic trace gases in the atmosphere, the characteristics of the dust and soil micro-environment and other local meteorological variables at the rover sites. Therefore, robotic precursor missions to Mars should accommodate environmental packages including radiation dosimeters. These data are required for a reliable risk assessment and for the establishment of protection guidelines for human missions to Mars.

Robotic lander missions should also provide test-beds for simple autonomous BLSS. This should include technological developments towards automation of bioreactors, including remote sensing; monitoring, including biosensors that would detect responses to stress at an early stage, or undesired

contaminants; biomass-concentrating, harvesting and processing technologies; and production, stability and management of microbial starters.

More knowledge is also required concerning bacterial growth, survival and colonisation (liquid and solid media, biofilms, attachment to surfaces including the external surfaces of the ISS) during long-term spaceflights and permanent planetary stations (waste and water recycling, production of oxygen and food). The ESA MESSAGE experiments are a step in this direction. For this purpose, the ISS is an ideal test-bed for studying the microbial ecology of a closed environment, comparable to an interplanetary and planetary habitat. Such studies should include the qualitative and quantitative characterisation of metabolic cycles and energetics of ISS-resident microorganisms; the detection, prevention and/or removal (elimination) of biofilm/biofouling and their associated microorganisms; the development/selection of appropriate materials that prevent biofilm formation (biotests, biocides, biofilters); the detection of pathogenic/opportunistic microorganisms (bacteria, viruses and fungi) from both human and environmental origins (air, surface and liquid samples, possibly food matrices), including their taxonomic identification (with molecular methods such as 16S rDNA), their response to radiation and the identification of relevant phenotypic and genetic characteristics (pathogenesis). This requires the development of specific space hardware, such as automated inoculation, sampling, monitoring and harvesting devices with the appropriate levels of containment. Microorganisms thus sampled from air, liquid or surfaces of the ISS, or directly from the astronauts' skin or clothes, should be retrieved for ground analyses of genetic drift/adaptation (for example, virulence genes or antibiotic resistance determinants) by mutation, rearrangement or horizontal gene transfers.

As far as the design of space bioreactors is concerned, crucial information is expected from experiments on the ISS concerning the production, stability and management of starters, the influence of microgravity on the transfer of gases inside the cultures, the stability and the productivity of the cultures, the interaction of radiation and microgravity as well as the monitoring and the prevention of undesired genetic or metabolic drifts. For studying combined effects of radiation and microgravity, the installation of an onboard radiation source would be needed. Many of these preliminary experiments, for example the influence of microgravity on microbial cell division, membrane integrity and viability, population shifts and genetic drift, could already be carried

out at the ISS now, employing small bioreactors and microbial communities (not merely with axenic cultures of single populations) which are essential for life support systems. A life support system which basically relies on the recycling abilities of microbial communities, needs to fulfil a number of requirements that should more or less guide the corresponding research agenda. The bio-systems approach for designing self-maintained life support systems should address the following criteria:

- Thermodynamic minimum criterion: What prevents the system from reaching thermodynamic non-equilibrium?
- Nutrient availability criterion: What are the sources of nutrients for assimilation and dissimilation? How are they recycled and what assures balanced nutrient composition to sustain growth?
- Diversity criterion: What is the population composition of the community? Are the necessary metabolic functions present?
- Ancestor-descendant criterion (phylogeny): Are the populations genetically related in such a way that some could replace some functions of others?
- Stability criterion: Are there enough “generalist” populations that could respond to changes in ecosystem determinants?
- Interdependency criterion: Is the system compatible with the presence of humans? Is it potentially pathogenic or sensitive to human-borne invasive species?

All behaviour or physiological studies on humans in confined (isolated) environments should include environmental studies on the dissemination of microbes between the inhabitants of the closed/confined environment, their interaction with surfaces and/or aerosols, and the occurrence of gene transfer. Concerning BLSS, ESA has supported their development for more than 15 years, based on the use of axenic microbial bioreactors and higher plants (the MELISSA loop). Substantial progress has been made on the engineering of the loop and the description of its kinetic properties. Ground research has to be continued and amplified to:

- improve the engineering of the BLSS
- close, as much as possible, the bioregenerative loop (bioprocess intensification in a continuous mode);
- ensure the integration of the different units and improve the connections between the compartments; to improve mass balance (water, nutrients and gas recycling);
- reduce the energetic requirements; and
- adapt to specific spatial constraints: reliability,

compactness, selection of materials (volume, weight, cleanability etc.).

To understand the biological effects of galactic cosmic radiation and its contribution to radiation health problems, such as cancer induction, irradiation experiments at heavy ion accelerators with mammalian cells will yield relevant empirical data. However, these experiments need to be performed at low fluxes that reflect the conditions in space. These conditions could be achieved by use of the now existing micro-beam facilities. In this case, the European facilities at GSI in Darmstadt and at Ganil in Caen, can provide appropriate irradiation opportunities. More accurate knowledge of the true response function for cancer induction at low exposure levels (single particle traversals) is required for radiation-protection considerations.

6.3.4. Summary of the recommendations

In appreciation of ESA’s support of exobiology research within the discipline astrobology and planetary exploration of the ELIPS programme, it is recommended that the following two goals in exobiology should be pursued in the future:

- the detection of signatures of life on other planets or other bodies, and
- the provision of supporting information required to enable human exploratory missions.

These two goals are well covered by the two cornerstones:

- *Origin, evolution and distribution of life,*
- *Preparation for human planetary exploration.*

To reach these research goals, actions should be taken by ESA as outlined in the following.

Recommendation 1

ESA should continue its efforts in exploring Mars which is considered the prime candidate for the detection of signatures of life beyond the Earth. ExoMars with its payload Pasteur and the three research goals (search for past life, search for present life, and hazards to humans) would ideally be the next step in this direction. These activities require an active planetary protection programme.

Recommendation 2

To explore Europa’s sub-ice ocean and its potential for habitability will be another important highlight in exobiology. As a first preparatory step, ESA should initiate a study on the habitability of Europa, its potential biota and suitable mission designs.

Recommendation 3

The abovementioned activities to search for signatures of life on other planets and bodies of our solar system must adhere to strict planetary protection rules. Therefore ESA should foster its planetary protection activities. The technological measures to prevent cross contamination of planets and other bodies during space exploration need to be further developed as we gain more and more knowledge about putative life on other planets of our solar system.

Recommendation 4

ESA should further foster exobiological research in Earth orbit by providing exposure facilities on the ISS and on autonomous free-flying satellites. Amendments of future facilities include the provision of a sun-pointing device and temperature controls that maintain sub-zero temperature during sun exposure.

Recommendation 5

Concerning the preparation of human exploratory missions, ESA should foster interdisciplinary cooperation within the ELIPS programme and with other relevant programmes. Contributions by the astrobiology and planetary exploration discipline include the development of life support systems including bioregenerative approaches; the early detection control and prevention of microbial contamination, and investigations of the radiation field in space and its biological effects. The studies require preparatory robotic space missions, use of the ISS, as well as supportive ground-based studies.

Recommendation 6

ESA should continue supporting research using ground-based facilities to gain information required for designing appropriate search-for-life experiments on Mars and Europa, and to elucidate potentially important pathways of prebiotic synthesis.

Recommendation 7

ESA should consider supporting field studies in regions which are suggested as terrestrial analogues of extraterrestrial habitats. This will allow the testing and validation of sensitive detection devices for signs of past and present life in the preparation of life-detection experiments on Mars and Europa and to train technicians and scientists involved in future planetary missions.

Recommendation 8

ESA should continue and extend its activities in outreach and education. In this context, the establishment of training opportunities in exobiology for PhD students and postdoctoral co-workers is recommended. This would contribute to building a space-oriented community, especially in the emerging field of exobiology which so far lacks training programmes at European universities. ESA should improve the publication of its research activities to a broad scientific community in order to be as competitive as possible on a European scale (for example via ESF to its member societies and/or the European Federation of Biotechnology (EFB)). ESA should improve its publicity regarding European activities in research in space; for example by producing more attractive websites, more press releases and television documentaries.

Chapter 7: Research in space – an integral part of general research

The question is often asked, how important is the added value of research in space compared to ground-based research in the same field? The scientific community is unanimously of the opinion that research in space should not be an esoteric, singular and little appreciated isolated discipline. It should provide unique added value to the broader field and therefore be evaluated in the general context of its parent discipline. Clearly, there are individual examples where space is uniquely necessary (for example in certain areas of astronomy where the atmosphere is not transparent in the wavelengths of interest, in areas where very long baselines are required and for all those situations where gravity imposes limits on precision, quality and the very existence of certain processes, both physical and biological. Similarly, if human space flights such as the planned Mars mission are continued, then medical research in space, materials research etc. must also be carried out to ensure the safety of those missions. Whilst the latter provides a goal in itself, and has a political “driver” as well as a basic research interest that extends beyond the immediate tasks of astronaut safety (for example, for exobiology), the former can – and has been – evaluated on a statistical basis by the Fraunhofer Institut für Systemforschung at the request of the German BMBF in July 2001. Here we summarise the salient findings from that evaluation (Potentialanalyse Forschung unter Schwerelosigkeit, Reiß et al. 2001) by permission of BMBF.

7.1. General development

The best quantitative indicator for assessing the general development – the growth – of a scientific field is the publication rate. This does not quantify the quality, of course, only the growth of interest in the field.

Figure 7.1 shows the total number of publications (solid line, in thousands), and the complementary research carried out in space (vertical bars). The points to notice are that:

- complementary research in space has increased in the years 1990–2000 from about 0.02% to 0.07% of the total (life and physical sciences added); and
- during this time the global publication rate increased by 40%, that of research in space by 280%.

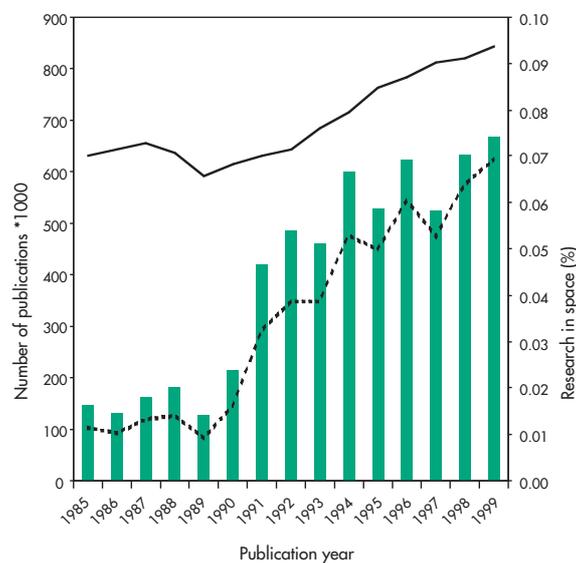


Figure 7.1: Number of international publications related to research in microgravity

Credits: BMBF and Fraunhofer Institut für Systemforschung, adapted from Reiß et al. (2001), *Potentialanalyse Forschung unter Schwerelosigkeit*, by permission of BMBF

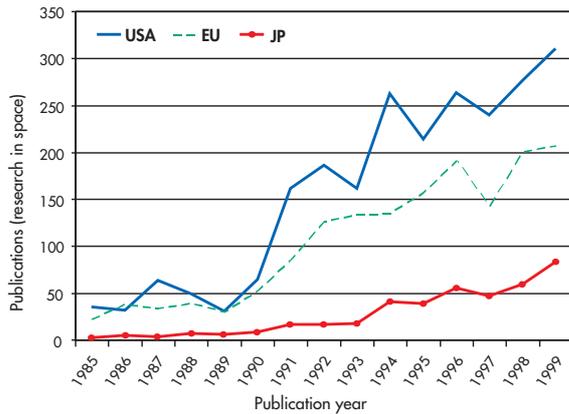


Figure 7.2: Comparison of the number of publications in the USA, Japan and the European Union

Figure 7.2 shows the publication record for research in space, separated by countries of origin (European Union, Japan, USA).

The USA's activities were largest, as is to be expected, but Europe stands immediately behind, with a comparable growth rate in the last 10 years.

7.2. Distribution according to disciplines

The major disciplines, as exemplified in the European ELIPS programme, are biology, medicine, materials (including fluid) science and fundamental physics (Figures 7.3 to 7.5)

The distribution of the publications shows that all four areas are roughly equally strong and productive, with perhaps a slightly higher emphasis in Europe on materials (plus fluid) science and fundamental physics, when compared to the USA.

7.3. Impact of research in space

Returning to the question of the importance of research in space, within the context of and complementing the broader ground-based research in the field, this is a notoriously difficult aspect of quantifying research impact generally. However, an objective procedure was used by the Fraunhofer Institut (Figure 7.6).

The technique is to compare the citation index of the publications in research in space with the corresponding citation index of the publications in the broader field – each normalised to their respective publication activity. The ratio of these two numbers is the relative citation impact (RCI):

$$RCI = \frac{\text{Citations/publication (research in space)}}{\text{Citations/publication (general broad field)}}$$

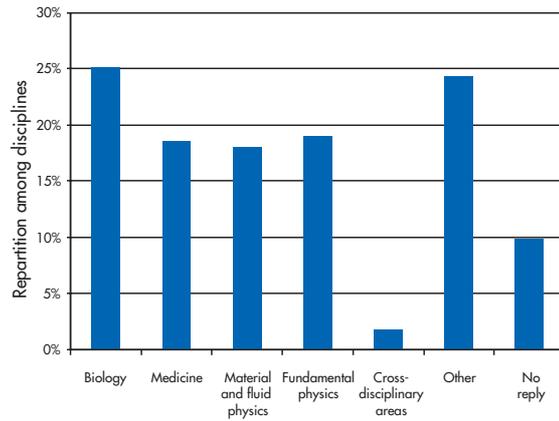


Figure 7.3: Repartition of publications among the various sub-disciplines – USA

Credits: BMBF and Fraunhofer Institut für Systemforschung, adapted from Reiß et al. (2001), *Potentialanalyse Forschung unter Schwerelosigkeit*, by permission of BMBF

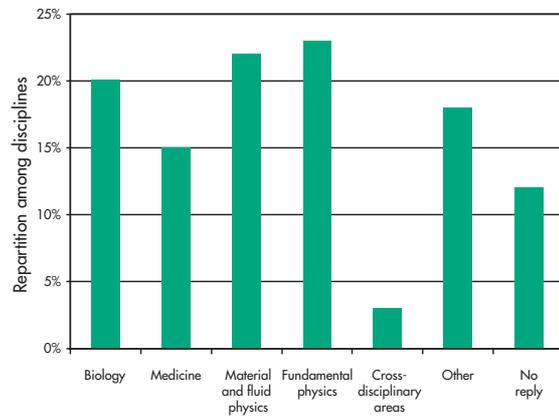


Figure 7.4: Repartition of publications among the various sub-disciplines – EU

Credits: BMBF and Fraunhofer Institut für Systemforschung, adapted from Reiß et al. (2001), *Potentialanalyse Forschung unter Schwerelosigkeit*, by permission of BMBF

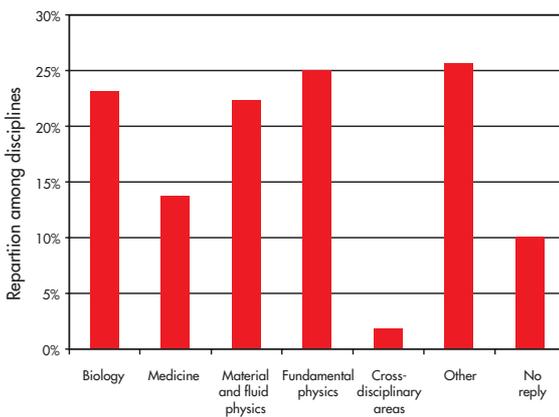


Figure 7.5: Repartition of publications among the various sub-disciplines – Japan

Credits: BMBF and Fraunhofer Institut für Systemforschung, adapted from Reiß et al. (2001), *Potentialanalyse Forschung unter Schwerelosigkeit*, by permission of BMBF

When this ratio is 1, the research in space may be regarded as equally important in the community as all the other publications in the general area. When it is above 1, its relevance may be regarded as higher.

The main conclusions from this analysis are:

- research in space has the same level of importance to the field as the research on the ground (for all the ELIPS activities combined.); and
- research in space has shown a continuous upward trend since 1990 in Europe, so that the RCI reached 1.1 between 1995 and 1999 (all ELIPS activities.).

Breaking this down into the various disciplines, and representing the information in a slightly different way, we can again assess the relative citation impact (Figure 7.6).

In Figure 7.7 the actual citation rate of the publications from research in space is plotted against the expected rate for the research field in general. For equal relevance of the two, the points should lie on the diagonal. The conclusion is again, that research in space has the same standing and carries the same weight (as measured by the citation impact factors) as the broader field in which it is embedded, for all individual fields in the ELIPS programme.

7.4. Conclusions

Although the impact analysis carried out for BMBF by the Fraunhofer Institut für Systemforschung analyses the data only up to the year 2000, the broad findings are still relevant even now, five years later.

- Research in space is fully embedded in the respective broader fields.
- It complements ground-based activities.
- It is of similar standing (as evidenced from the citation impacts).
- Its impact is growing steadily.
- Europe plays an important role worldwide, in its position of direct challenger to the USA, with a strong possibility of becoming world leader provided the current support is continued.

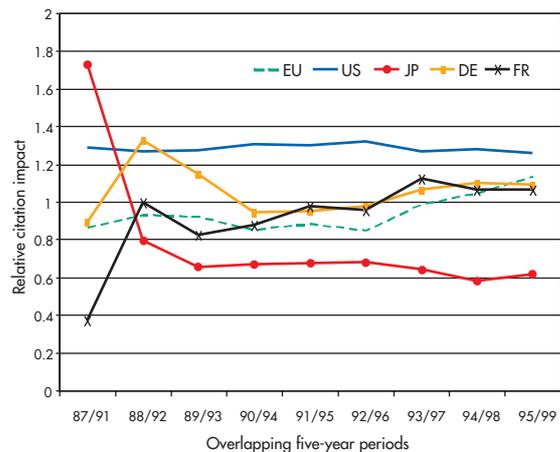


Figure 7.6: Comparison of the relative citation impact in various countries and in the EU

[The data refer to overlapping five-year periods (x-axis). Publications and citations are collected for this time period]

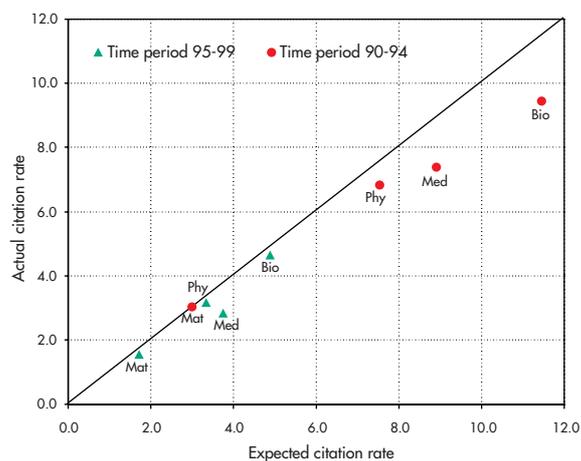


Figure 7.7: Observed versus expected citation index compared between disciplines

Credits: BMBF and Fraunhofer Institut für Systemforschung, adapted from Reiß et al. (2001), *Potentialanalyse Forschung unter Schwerelosigkeit*, by permission of BMBF

Chapter 8: Appendices

Appendix 8.1. Bibliography and references

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8.2.3. Synthesis workshop

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Appendix 8.3. ESSC members (April 2005)

Chair

Gerhard Haerendel	<i>International University Bremen, Germany</i>
Willy Benz	<i>Universität Bern, Switzerland</i>
Bernard Billia	<i>L2MP University Aix-Marseille, Marseille, France</i>
Roger Bouillon	<i>KU Leuven, Belgium</i>
Bruno Carli	<i>IFAC-CNR, Firenze, Italy</i>
Angioletta Coradini	<i>IFSI-CNR, Roma, Italy</i>
Pascale Ehrenfreund	<i>Leiden Observatory, Leiden, Netherlands</i>
Jean-Louis Fellous	<i>IFREMER, Issy-les-Moulineaux, France</i>
Monica Grady	<i>Natural History Museum, London, United Kingdom</i>
Eberhard Grün	<i>MPI für Kernphysik, Heidelberg, Germany</i>
Peter Norsk	<i>Panum Institute, Copenhagen, Denmark</i>
Jean-Loup Puget	<i>Institut d'Astrophysique Spatiale, Orsay, France</i>
Sabine Schindler	<i>Institut für Astrophysik, Universität Innsbruck, Germany</i>
Christiane Schmillius	<i>Dpt. Of Geoinformatics, FSU Jena, Germany</i>
Kai-Uwe Schrogl	<i>DLR, Köln, Germany</i>
Catherine Turon	<i>GEPI, Observatoire de Paris-Meudon, France</i>
Michel Vauclin	<i>LTHE-ENSHMG, Grenoble, France</i>
ESF Executive Scientific Secretary	
Jean-Claude Worms	<i>ESF Strasbourg, France</i>

List of acronyms

ACES	Atomic Clock Ensemble in Space
CNRS	Centre National de la Recherche Scientifique
EEA	Erasmus Experiment Archive (ESA)
ELIPS	European Life and Physical Sciences and Applications in Space programme
EML	Electro-Magnetic Levitator (ESA/ISS)
EMRC	European Medical Research Councils (ESF)
ESA	European Space Agency
EXAFS	Extended X-ray Absorption Fine Structure
GANIL	Grand Accélérateur National d'Ions Lourds (Caen, France)
GSI	Gesellschaft für Schwerionenforschung mbH (Darmstadt, Germany)
HUMEX	Study on the survivability and adaptation of HUMans to long-duration EXploratory Missions
ICAPS	Interactions in Cosmic and Atmospheric Particle Systems (ESA/ISS)
IMPACT	International Microgravity Plasma and Cosmic Dust facility (ESA/ISS)
IMPF	International Microgravity Plasma Facility (ESA/ISS)
IMPRESS	Intermetallic Materials Processing in Relation to Earth and Space Solidification
ISS	International Space Station
LEO	Low-Earth Orbit
LESC	Life, Earth and Environmental Sciences Standing Committee (ESF)
LTE	Local Thermodynamic Equilibrium
MAP	Microgravity Application Programme
MSL	Materials Science Laboratory (ESA/ISS)
NASA	National Aeronautics and Space Administration
PB-HSR	Programme Board for Human Spaceflight and Research (ESA)
PESC	Physical and Engineering Sciences Standing Committee (ESF)
PHARAO	Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite
PKE, PK-3, 4	Plasma Krystall Experiments
RPM	Random Positioning Machine
SEM	Scanning Electron Microscope
STS	Space Transportation System (Space Shuttle)
UHV	Ultra-High Velocity
USOC	User Support and Operation Centre



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