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→ ROADMAPS FOR FUTURE RESEARCH

A redefinition of strategic goals for future space research on the ISS and supporting research platforms

European Space Agency

FOREWORD

The Science Department of ESA's Human Spaceflight and Exploration Directorate has undertaken an extensive exercise to create a new strategy, focussing on a set of newly defined goals. This will help to positively shape the future research programme of the Directorate and maximise research potential. This all-embracing process culminated in a three-day consultation workshop in January 2016, pooling the combined expertise of ESA together with the foremost scientific and industrial expertise across Europe.

This new set of strategic goals covering all areas of research in the in the life and physical sciences have been laid out in scientific roadmaps which are presented in this document. By opening up the strategic process to the wider scientific community it has been possible to clearly define the most important goals currently facing science and the global economy and present them in a coherent way. The roadmaps now provide a clear framework within which a fully comprehensive and scientifically valuable programme with exceptional, but highly achievable, goals can be achieved.
The process of creating the roadmaps has involved hundreds of individuals from the wider science and engineering communities and from inside ESA. Their contributions have been invaluable in bringing this process to a successful conclusion.

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GENERAL INTRODUCTION

The global goals of humanity are evolving as we redefine the strategic goals for securing and improving the welfare of the planet and its ever-aging population whilst creating an ever-sustainable and efficient industrial sector based on factors such as improved processes, optimal use of natural resources, reducing consumption and improving recycling. Similarly the strategic goals of human spaceflight are evolving, moving inexorably towards exploration beyond low-Earth orbit. This global endeavour encapsulates the deeply rooted quest of humankind to answer questions on the origins of life on Earth and its possible presence on other planets, extend the limits of our knowledge, and eventually expand human presence in the solar system.

Science will provide solutions to many of the challenges at the heart of this evolution in space and on Earth, and the European Space Agency (ESA) has taken a major step in redefining science activities to meet these challenges. ESA's Human Spaceflight and Robotic Exploration Directorate facilitates the most diverse areas of scientific enquiry and a new strategy has been developed together with the broader European research community to guide the Directorate's science programme to maximise future research potential. The objectives are aligned with the major strategic goals facing the planet on earth and in space as defined in: the ESA space exploration strategy which was endorsed by ESA Member States at the 2014 Ministerial Council; the THESEUS (Towards human exploration of space: a European strategy) Roadmap developed by the European Science Foundation as a coordination activity with the European Commission; and the global goals for sustainable development, adopted by the United Nations in September 2015. The new approach also takes into account the guiding principle that fundamental research is always at the heart of best science whether for improving knowledge or for feeding into processes and applications.

The research goals of this new strategy, which aim to address specific objectives by 2024, have been defined in 10 unique scientific roadmaps in the life and physical sciences which are presented in this document. These roadmaps are the core of the proposal of a new science programme called "Science in Space Environment" or SciSpace which will form part of a proposal put forward at ESA's Council at Ministerial Level meeting in December 2016. This new strategy will allow for synergies to be found as different areas of science work towards the same overarching goals from different perspectives. It will also allow for the different nations and agencies within Europe and globally to gain the benefits and flexibility from participating in different research projects whilst at the same time working towards the same strategic goals as their neighbours.

ESA's already has many fundamental and applied research projects in its current pool of experiments which can address many of the new strategic goals. This new set of goals also creates the framework to attract new research projects from Europe and worldwide to tackle and fulfil all other strategic goals set. Couple this with an extensive depth of research hardware already in orbit on the International Space Station (ISS) and a broad spectrum of complementary research platforms available to ESA and this offers the potential for a very positive new science programme for tackling all of the strategic objectives defined in the short- , medium- and longer terms. This would provide continuity to the end of the lifetime of the ISS into the next decade and beyond. This is further compounded by a new optimised cost approach which will maximise research return and provide more clarity in, and control of, required resources by assessing the end-to-end process at the experiment selection phase.

ROADMAP 1: A ROADMAP FOR FUNDAMENTAL PHYSICS IN SPACE

1.1. Foreword

Measuring and experimenting have been at the heart of the physics approach to understand Nature. Measurement has reached unprecedented levels of refinement, requiring very special conditions, in the last part of the 20th century. Space often provides such a clean environment, whether it is for very precise measurements of time and distance, the motion of massive bodies and light propagation, the identification of the tiny deformations of our space-time associated for example with the propagation of gravitational waves, or the clean detection of cosmic particles of high energy.

Pushing measurements to their limits, it is therefore not surprising that fundamental physics research in space lies at the forefront of our knowledge and tests the two fundamental theories that are the legacy of the 20th century: general relativity and quantum theory (in the form of the Standard Model for microscopic fundamental interactions). The Einstein equivalence principle is a cornerstone of the theory of general relativity, which celebrated very successfully its 100th birthday in 2015. The fact that these two theories are notoriously difficult to reconcile makes this programme an even more exciting challenge.

One may group the searches associated with this programme under two intimately connected areas of research:

- **Tests of fundamental laws:** tests of fundamental principles, in particular the equivalence principle (weak equivalence principle, local Lorentz invariance and local position invariance including constancy of constants), tests of the law of gravity at all length scales, as well as in its weak or strong regime, structure and dimensionality of space time, tests of the foundation of quantum mechanics,
- **Search for fundamental constituents:** scalar fields for dark energy, particles for dark matter, fundamental strings, etc.

In 2010, the Fundamental Physics Roadmap Advisory Team (FPR-AT) was convened by ESA in order to draw up recommendations on the scientific and technological roadmap necessary to lead Europe toward the realization of future space missions in the framework of the Cosmic Vision 2015-2025 plan in the field of fundamental physics. After an in-depth consultation with the Fundamental Physics community, FPR-AT released its final report "A Roadmap for Fundamental Physics", 26 July 2010 (see http://sci.esa.int/fprat). The topics discussed in that document as well as the final recommendations remain very actual. Today, we intend to revisit the document produced by FPR-AT in 2010 and update it in the light of the recent progress in the field. The document specifically addresses three major topics:

- Testing the foundations of gravitational physics with clocks in space;
- Atom interferometry tests of the Weak Equivalence Principle;
- Ultra-high energy research from space.

1.2. Specific Objective A: Testing the Foundations of Gravitational Physics with Clocks in Space

1.2.1. Introduction

Albert Einstein's theory of general relativity (GR), which celebrated its 100th anniversary in 2015, is a highly successful theory of one of the four fundamental forces in nature. It is widely applied to understand the structure of our universe on hugely different space and time scales. Applied to special systems such as pulsar double stars, it provides an accurate test of its validity, in particular as far as strong gravity effects and dynamic effects (including gravitational waves) are concerned.

Physicists are deeply interested in testing GR in order to probe whether it is really a "perfect" description of gravity. Indeed, it is expected not to be, since it is not unifiable with quantum physics. Tests of GR have been done by observing various astrophysical phenomena, in particular the double-star pulsars. Precision measurements of the deflection of light and the time delay of light signals by massive bodies have been and are being performed by space missions (Cassini, Gaia).

It is also possible to perform experimental tests, where custom-built instruments are placed in a controlled setting. Mostly, these experiments are devoted to testing the foundation (assumptions) of GR, in particular the weak equivalence principle (WEP), which states the equivalence of inertial and gravitational mass. After decades of laboratory experiments with torsion balances, in 2016 a space mission, MICROSCOPE, will attempt to test the WEP in a specially designed, drag-free satellite, with goal sensitivity of 1 part in 10^{15}. Such experiments using macroscopic masses are complemented by experiments using cold atoms, e.g. in an optical lattice or in free-fall in small or tall towers (10 – 100 m), and even proposals for space experiments have been made.

Another aspect of the foundations of GR is that gravity affects time. Time flows differently in different gravitational potentials, an effect called gravitational time dilation or gravitational redshift. At the lowest order in the gravitational potential U, this effect represents one aspect of the strong equivalence principle. At higher order, time dilation arises from the specific form of the component g_{00} of the metric tensor of space-time, and is nonlinear in the potential U.

In more explicit terms, GR predicts that observers at different gravitational potentials experience different clock rates, even if they use exactly the same clock type. However, the observers realize this only if they communicate with each other, sharing information about how often their clocks have ticked during a common time interval defined by a start and an end signal. This information sharing is accomplished by a frequency transfer link.

The redshift effect has been verified in several specifically conceived experiments, at various levels of accuracy. It has also been found to be crucial to include this effect in the synchronization of the constellation of orbiting clocks used for the world-wide global positioning systems with Earth-based clocks. It has also been observed on a quartz oscillator in a spacecraft moving through the solar system. Finally, it has been observed on spectral lines in the sun's spectrum (with percent-level accuracy) and in astrophysical phenomena.

The most precise measurement of the gravitational redshift so far has been at 1.4×10^{-4} fractional inaccuracy level (Gravity Probe A mission), realized by comparing two hydrogen masers at 1×10^{-14} frequency uncertainty level, where one maser was launched into space on a rocket, to a maximum vertical height of 10 000 km, while the reference maser clock remained on Earth.

This nearly 40-year-old experiment is still the most precise direct test of the gravitational time dilation. The need to improve on the above test result has motivated many researchers towards proposing new space missions. Most importantly, in 2017, the Atomic Clock Ensemble in Space (ACES) space mission will be flown on the ISS. Here, a microwave cold atom clock will be used, which was designed to reach a goal inaccuracy of 3×10^{-16}. Flying at an altitude of 380 km, the experiment will test the time dilation at the level of 2×10^{-6}, a 70-fold improvement in sensitivity compared to Gravity Probe A.

The developments in the field of atomic clocks in the last 15 years have opened up new possibilities to test the foundation of GR. Indeed a new generation of atomic clocks has been established, the optical atomic clocks. They have been made possible by the development of lasers with superb spectral purity, of subtle atom manipulation techniques, and of the femtosecond frequency comb technique, techniques which were awarded several Nobel prizes in recent decades.

The potential of the optical clocks relies on the access to atomic transitions in the optical domain ($\nu_o \approx 10^{15}$ Hz) having a natural linewidth $\delta\nu_o$ of a few mHz, corresponding to a transition quality factor Q= $\nu_o / \delta\nu_o$ orders of magnitude higher than achievable in microwave standards. In the last few years this potential has been expressed, with groups demonstrating for the first time fractional stability and accuracy down to the 2×10^{-18} level. This level is a factor of approximately 100 better than obtainable with the best microwave atomic clocks. In fact, it seems possible to go even beyond this level in the near future.

It is clear that optical clocks, present implementations and emerging ones, will allow tests of GR of unprecedented accuracy in the near and distant future. In addition, they are also excellent tools for applied measurements.

1.2.2. Present Status

Clocks On Ground versus In Space: Expected Developments In The Next Ten Years

While clocks with 1×10^{-18} inaccuracy seemed a decade away at the time of writing of the 2010 roadmap, after only half that time, the first national metrology labs are within factors of 2 of this level, with the strontium (Sr) lattice clock, the ytterbium (Yb) lattice clock and the Yb single ion clock. Strong further progress is expected and ground clocks may reach the low 10^{-19} range in the next 10 years, thanks to the large number of quantum optics and laser specialists contributing to the development worldwide, especially in Europe, US, Japan, and China.

An impressive example of the performance of optical lattice clocks was recently given in Japan, where an optical lattice clock at RIKEN (Tokyo) was compared with a similar clock at the University of Tokyo, located at 10 km distance and linked by optical fibre. The clock frequency difference measured was -709.5(28) mHz (corresponding to a relative uncertainty of 6.5×10^{-18}). This is in agreement with the expected redshift due to the gravitational potential difference, which was independently measured by levelling techniques, -707.48 mHz due to the 15 m height difference. This experiment already achieves an inaccuracy of 4×10^{-3} in testing the redshift. Considering that the height differences was really small, the achieved inaccuracy puts into evidence the tremendous potential of the optical clock technique, if the large height differences that space provides can be made use of.

Strong progress is also occurring on implementing ultraprecise optical clocks capable of operating outside of the few advanced metrology laboratories, a remote possibility at the time of the 2010 roadmap. In Europe, already three transportable optical lattice clocks have been developed, of which one has already been transported between countries. The vision of availability, ten years from now, of a large set of optical clocks with 10^{-19} – level performance that can be transported and operated anywhere on Earth is becoming realistic.

This progress has implications for space missions with optical clocks:

- The mission will need to provide links capable of comparing ground clocks at the 10^{-19} level in a moderate integration time, the ground clocks being located anywhere on the Earth;
- The number of ground clocks available for inter-comparisons will be large (> 20);
- The improving accuracy of ground clocks implies that more accurate tests of the gravitational redshift become possible when comparing ground clocks with space clocks;
- The technological and scientific developments occurring for ground clocks facilitate the development of a space clock prototype and promise performance beyond 1×10^{-17} for the actual flight model (goal delivery date: 2023). This will enable more accurate tests of the gravitational redshift and more accurate time distribution than foreseen in 2010.

Atomic clocks in space: Scientific Potential

The strong progress in the field of optical clocks since the time of the 2010 roadmap has rendered the goal of realizing a space optical clock with 1 x 10^{-17} inaccuracy within 2020 even more realistic. In fact, a performance beyond this level can be expected, given that the issues that limit clock accuracy are much better understood today than five years ago, and appropriate corrective measures can be implemented in the space clock design. Given that the most realistic flight option is the ISS, the first space optical lattice clock to be developed will be of the lattice type, providing low instability already on short timescale, with physical parameters (mass, volume, power consumption) similar to those of ACES.

Following the evolution of laser and atomic technology, it is expected that eventually a high-accuracy optical clock could also be realized with moderate physical parameters (< 50 kg, < 200 W, < 500 litre), opening the possibility of flying it on satellites other than the ISS, in particular on highly elliptic orbits or to the inner part of the solar system, with much larger gravitational potential differences.

Furthermore, the technology development also opens the perspective of operating a space clock with two different atomic species, with moderate extra cost in terms of physical parameters, enabling in addition tests of Local Position Invariance.

With space clocks of 10^{-17} – 10^{-18} inaccuracy, the accuracy of the test of the gravitational redshift increases as a function of the orbit size and type (due to an increasing gravitational potential difference). While for Earth-bound orbits the term of the redshift effect that is linear in the gravitational potential can be tested, for orbits with segments close to the Sun also the quadratic contribution becomes testable. This represents a qualitatively new regime for redshift tests.

Optical clock on the ISS (mission candidate SOC; see Table 1.1):

Open fundamental science question	Focus of space experiment	Relevant research topic	Related recent and future space experiments
Is General Relativity the correct description of the physics of gravitation?	Measure the time dilation in the gravitational field; Make use of the large differences in gravitational potential in space.	Frequency comparisons between atomic clocks.	ACES (2017) MICROSCOPE (2016)
Is Lorentz Invariance an exact symmetry of nature?	Measure spin-dependent energies in cold atoms; make use of the large velocity of the ISS.	Precision laser spectroscopy.	ACES (2017)
Do so far undiscovered new forces exist in nature? Do the fundamental constants change in time? Do new forces influence the tick rates of clocks?	Allow the inter-comparison of a large number of atomic clocks on the ground over intercontinental distances.	High-precision time/frequency links between ground and ISS.	ACES (2017) MICROSCOPE (2016)

Table 1.1: Fundamental questions to be studied by the mission SOC on the ISS

- Test of the gravitational redshift in the Earth field with up to 100 times higher accuracy than ACES;
- Test of Local Position Invariance in the Earth gravitational field with up to 100 times higher accuracy than ground experiments;
- Test of gravitational redshift in the Sun field with up to 10 times higher accuracy than with ACES (thanks to the advances in accuracy of ground clocks beyond the ACES time frame). These different experimental implementations allow searching for a non- universal coupling between matter;
- Worldwide comparison of ground optical clocks using the Space Optical Clock (SOC) laser links, with applications to e.g. relativistic geodesy down to the 1 mm height resolution level (with improvements in modelling of relativistic frequency transfer and orbital motion);
- Search for new physical fields which couple to ordinary matter leading to clock frequency variations of different type;
- Dissemination of time and frequency worldwide, with sub 10^{-17} inaccuracy, on the time scale of a single pass of the ISS. Dissemination can be to ground or to tropospheric/ stratospheric platforms

Optical clock on a highly elliptic orbit around Earth

- Test of the gravitational redshift with up to 1000 times higher accuracy than ACES;
- Test of Local Position Invariance in the Earth gravitational field with up to 1000 times higher accuracy than ground experiments (with a two-species clock);
- Worldwide comparison of optical clocks, with applications to e.g. relativistic geodesy at the 1 mm level, and supporting progress in optical clock development;
- Dissemination of time worldwide, with sub 10^{-17} inaccuracy, to a vast range of users.

Optical clock on an orbit to Mercury

- Test of the gravitational redshift in the Sun gravitational field with up to 10^8 times higher accuracy than previous space missions/solar spectroscopy;
- Test of Local Position Invariance in the Sun gravitational field with up to 100 times higher accuracy than ground experiments (with a two-species clock).

Test of light propagation in the gravitational field (Shapiro time delay, light deflection)

The concept of a space mission performed with high-accuracy optical clocks, was analysed by P. Bender and colleagues (JILA, USA). It requires two drag- free spacecraft, one of which is a laser transponder, the other carrying the optical clock. The goal is a determination of the PPN parameter γ with inaccuracy in the 10^{-8} range. The ongoing clock developments may render such a mission feasible in two decades. It has recently been suggested to consider whether this test and a test of the solar redshift at Mercury distance could be combined in a single mission, possibly reducing the overall cost. The clock-carrying satellite would be sent on an orbit that brings it into conjunction with the sun and also includes a fly-by of the Sun.

Atomic clocks in space: Technological and Interdisciplinary Potential

Atomic clocks are by far the most precise instruments. They can be applied to a range of measurements which span from spacecraft and aerial vehicle navigation to geophysics. These applications, which are very well adapted to the ISS as the carrier of an optical clock, are summarized in Table 1.2.

Applied Science Challenge	Focus of space experiment	Relevant research topic	Related recent and future space experiments
Increase the accuracy of the determination of the geoid (higher spatial resolution, lower inaccuracy).	Allow the inter-comparison of transportable atomic clocks on the ground spaced by distances from regional to intercontinental scale.	Frequency comparisons between atomic clocks.	GOCE (2009) ACES (2017) GRACE-FO (2017)
Monitor the time-dependence of the geoid.	Allow the inter-comparison of transportable atomic clocks on the ground spaced by distances from regional to intercontinental scale.	Frequency comparisons between atomic clocks.	GOCE (2009) GRACE-FO (2017)
Improve navigation accuracy of interplanetary spacecraft.	Demonstrate next-generation time/frequency links and atomic clocks.	Reduce physical parameters of next-generation atomic clocks; extend optical laser links to large distances.	
Improve navigation accuracy of stratospheric platforms.	Provide ultra-stable frequency to and distance measurements to and between stratospheric platforms, worldwide.	Frequency comparisons between atomic clocks.	
Deliver high-accuracy time and frequency everywhere on Earth and in space	Provide ultra-stable frequency to worldwide users, on the ground, in the atmosphere and in space.	Optical atomic clock in space and optical link.	ACES (2017)

Table 1.2: Applied science studies to be performed by the mission SOC on the ISS

1.2.3. Priorities for the Space Programme

Development of optical clocks for space applications

The 2010 roadmap presented the beginning developments of optical clocks for space. In the meantime, these developments, organized by the SOC consortium, have borne fruit and are continuing at an even more rapid pace.

- Two lattice clocks developed by the SOC consortium (a Yb lattice clock and a Sr lattice clock) in the framework of an EU-FP7 project have been transported between countries, and have produced cold atoms again within days of arrival. The Sr lattice clock from the SOC consortium, the most compact lattice clock to date, has overall parameters 500 kg, 1.1 kW, volume of 3 racks. It must be stressed that it was not attempted to minimize these parameters. Robust transportable reference cavities with (1-3) x 10^{-15} frequency instability have also been demonstrated. Finally, the robustness of high-finesse mirrors against proton irradiation has been demonstrated.
- US scientists are currently funded by NASA to conduct collaborative research with European colleagues for the ESA SOC programme.
- After the end of FP7, the development of these systems is continuing and well-staffed. It is funded in part by the Initial Training Network ITN-FACT (coordinated by K. Bongs, member of SOC consortium), and by the academia-industry cooperation project Q-SENSE in the Horizon 2020 programme RISE (coordinated by K. Bongs).
- The Italian space agency ASI is funding a development project for subsystems of a Sr lattice clock, in particular a 3rd generation atomics package (2016-18). This is a cooperation between the University of Firenze (G.M. Tino) and space industry (Kayser Italia).
- A frequency comb has successfully been flown on a rocket in 2015 (mission FOKUS, funded by DLR), demonstrating robustness. Compact frequency combs are now commercially available from two European companies.
- Frequency comb development by European laser companies is strongly pushed by the demand of scientific customers and in addition is funded by the US Defense Advanced Research Projects Agency (DARPA) at international level.
- Demonstration of a radiation-hard femtosecond laser.
- Shock-resistant wavemeters have been demonstrated by a European company.
- Following detailed consultations with the SOC consortium, ESA has initiated technology development of subsystems of a Sr lattice clock: 461 nm laser, 689 nm laser, 813 nm laser, and a corresponding frequency stabilization unit. These units will reach TRL 5. These projects will be implemented in 2016-17 by consortia in which research groups from the SOC consortium cooperate with industrial partners.
- In another ESA-sponsored technology development, a “high-stability laser” has been developed in a cooperation between space industry and a metrology laboratory (NPL). It includes a compact, robust ULE reference cavity with accurate long-term temperature stabilization.
- Commercially available laser systems are getting simpler and more robust. Blue semiconductor lasers at 461 nm (for Sr), interference-filter lasers for various wavelengths, suitable in particular for optical clocks, efficient waveguide frequency doublers, all were non-existent in 2010 but are now available products. These developments represent the foundation for upcoming space qualification, and promise an important reduction in risk and cost. Beyond these subunits, other space-qualified components, such as waveguide electro-optic modulators, have become available.
- A new development is crystalline mirror coatings, which promise a reduction of the thermal noise level of the reference cavities, leading to enhanced performance of optical clocks in general, and space clocks in particular.
- The development of new measurement protocols to reduce the contribution of the laser noise.
- Some members of the SOC consortium are also members of the ACES consortium, ensuring continuity of know-how.
- Some members of the SOC consortium are also intensely engaged in the development of laboratory (stationary) optical clocks towards ultra-high performance and their inter-comparison via optical fibre links, thus providing continuous input to the consortium at the highest scientific level.

Recommendations for the development of space optical clocks:
The recommendations given in 2010 have been put into practice essentially as stated at the time, with developments having been funded by the EU, ESA, national agencies, and also driven by non-space applications. The decision has been made to focus on the strontium lattice clock. For the near future (2017-2020), we recommend:

- ESA/national agencies/EU/ERC to support developments of the cooling and lattice lasers mentioned above from TRL 5 further to TRL 7.
- ESA/national agencies/EU/ERC to initiate the development of the remaining subunits for a Sr lattice clock to TRL 7: (i) clock laser; (ii) re-pumper lasers; (iii) electronic control system; (iv) 4th generation atomics subsystem (v) frequency comb capable of 10^{-19} performance.
- ESA to start as soon as possible a phase-A study of the mission SOC on the ISS.

Development of optical links

The development of fibre-optic links in Europe has made spectacular progress: link lengths are now at the 1000 km scale, and a network connecting the UK, France, Germany, Italy, and other countries is being set up and tested. For example, the international optical fibre link between PTB (Braunschweig) and SYRTE (Paris) is operational since April 2015. It has led to the demonstration of the agreement of two optical lattice clocks with accuracies in the low 10^{-17} range.

The rapid improvement of atomic clocks on ground toward the 10^{-19} inaccuracy level implies that for space missions that seek to compare distant optical clocks on ground in 8-10 years from now, a link technology with sufficient accuracy should be foreseen. The microwave link (MWL) and the European Laser Timing (ELT) optical link, to be used on ACES, are expected to reach the 10^{-17} level, not sufficient for the SOC mission. This leads to the need to initiate the development of high-performance optical ground-to-space links. Indeed, a revolutionary optical link technique has been demonstrated in 2013-15, which opens up a new performance window. The technique, developed by N. Newbury and collaborators at National Institute of Standards and Technology (NIST), is based on two-way (i.e. round-trip) signal transfer of pulses from mode-locked lasers. The mode-locked lasers are actually self-referenced frequency combs, of which one comb line is locked to the clock laser frequency of the respective optical clock. The performance of this link type is outstanding. The NIST group has already demonstrated a timing inaccuracy of 1 fs over 10000 s integration time for a 4 km air path parallel to ground at an altitude of 2 km (Boulder, Colorado), corresponding to 1×10^{-19} frequency comparison inaccuracy over this timescale. Remarkably, this technique is robust to link interruption and link length variations, e.g. caused by turbulence.

The 4 km horizontal air path already demonstrated in Boulder is roughly equivalent to the influence of the atmosphere that will have to be traversed by a laser beam going from ground to the ISS (or vice-versa), because the density of the atmosphere has a 1/e length scale of 9 km and in addition turbulence decreases strongly with height above ground.

Work of the NIST group continues under DARPA and NIST funding in order to extend the link's range (current experiments investigate 11 km long link), robustness, and its operation to moving platforms. The ultimate motivation for this research on the optical link is to support the ground-breaking space-based fundamental science programme of SOC.

On the timescale of one ISS pass (300 s), the demonstrated timing inaccuracy is 0.6 fs, corresponding to 2×10^{-18} uncertainty for frequency comparisons. If this level can actually be implemented in a ground-to-space link with a moving space target such as the ISS, an optical clock on the ISS could be compared with a ground clock at its expected inaccuracy already during a single pass. Feasibility (reciprocity of the two-way link) might be enhanced by splitting the link into two parts: ISS – stratospheric platform (without influence of the atmosphere, but large relative velocity) and stratospheric platform – ground (with influence of the atmosphere, but small relative velocity).

There is also significant activity in the field of robust laser terminals for high-speed optical data transfer, outside of the space industry. This activity is driven by commercial data transfer applications in the stratosphere. There, robustness requirements are in part similar to those for space. However, this more commercial activity, with expected large unit number production, promises to lower unit costs significantly. Performance-wise, the laser terminals have been shown to allow Gb/s data rate communication between ground and a jet plane and for distances of up to 60 km. For laser data transmission between stratospheric balloons, distances in the order of 250 km are foreseen to be covered. Achieved specifications are operating temperatures between –80 deg C to +40 deg C, 5 kg mass and 50 W power consumption. These physical parameters are intriguing also for satellite/ISS applications. A preliminary analysis indicates that the integration of such terminals with frequency combs sources is definitely possible.

Cooperation with US teams

The NIST team of SOC (Boulder, USA) will be able to support SOC in two ways. Firstly, through continued progress on clock research itself. Lattice optical clocks at NIST have reached ever-increasing levels of performance over the years. Recent experiments have demonstrated a fractional clock instability as low as $10^{-16}\,(\tau/1\,\mathrm{s})^{-1/2}$, averaging down to below 2×10^{-18} for $\tau = 20000$ s. The NIST team anticipates further reduction of this value in the coming years.

The NIST team will also contribute to remote clock comparisons during the ACES mission, establishing important know-how for the later SOC mission.

Secondly, the optical link development will be supported, under DARPA and NIST funding, in order to extend the link's range, robustness, and its operation to moving platforms.

1.2.4. A Set of Recommendations

In the near term period 2016-2020

- ESA is fully engaged in the ACES mission. ACES will indeed pioneer the field of high precision time and frequency metrology from space, providing unique tools for testing the Einstein's theory of general relativity. Therefore, we recommend ESA to ensure full support to the ACES mission until launch, during operations, as well as during the mission exploitation phase.
- The rapid development of transportable optical clocks also opens new opportunities of experiments and tests during the ACES mission (2017-2020). The transportable clocks could, for example, be operated in African or South-American locations. Therefore, it is recommended that ESA provides a transportable MWL and a transportable ELT ground terminal, and other necessary hardware, for at least part of the ACES mission duration, to a consortium that will operate transportable optical clocks.
- It is recommended that a phase A study for the SOC mission is run in 2016 and that all necessary technology developments are completed in the time-frame 2016-19, with the goal of establishing full feasibility of the mission. This includes the technology of the optical clock itself and of an enhanced version of the microwave link (MWL), for which an ESA study is currently under way.
- It is further recommended that in 2017 a development effort be started by ESA/national agencies on free-space, ground-to-space links, which promise exceptional performance, capable of satisfying the most optimistic inaccuracies required for ground-to-space clock comparisons and ground-to-ground clock comparisons.

In the medium term period 2020-2024

- Phases B and C should follow in the time frame 2020-2023, with a possible launch date of SOC on the ISS in the 2023-2024 timeframe.
- It is recommended that from 2020 on, technology development for the next-generation optical clocks, having both significantly reduced physical parameters (mass, volume, power consumption) and increased performance compared to the SOC clock, be undertaken. This will enable next-generation fundamental missions with clocks, including where a clock on the ISS will be compared with a clock on a more distant satellite in an Earth orbit or in an orbit approaching the Sun. The reduced physical parameters of future clocks will make missions with custom satellites less expensive.

1.3. Specific Objective B: Atom Interferometry Test of the Weak Equivalence Principle

1.3.1. Introduction

The unification of gravitation, or more precisely general relativity, and quantum theory is one of the most fundamental quests in physics. In particular, it postulates a universal, i.e. a structure and composition independent, free fall for all matter at the same point in space-time. As postulate, this statement is under continuous scrutiny and continuously challenged by torsion-balance experiments, lunar-laser ranging and in the near future by the satellite mission MICROSCOPE for classical test bodies in order to get hints for additions to our incomplete description of nature.

Experiments based on matter-wave interferometry will probe this principle for the first time with quantum objects of large coherence length. Quantum tests of free fall constitute a qualitatively different experimental approach, where the different pillars of the equivalence principle merge. With that respect, they are very attractive for a variety of reasons. Examples are the recent redshift controversy or the possibility to use quantum systems to probe different features or properties of the physical space-time than classical bulk matter. With quantum systems, other degrees of freedom, different from classical ones, like elementary particle spin are also available providing a different insight into the exploration of space-time geometry.

Moreover, the rapid evolution of quantum engineering is now opening up fascinating perspectives for tests of the validity of the postulate with improved accuracy. Therefore, many experimental activities recently started to advance those experiments.

1.3.2. Advantages of Space

The time of free fall is a key parameter and its extension is the motivation not only for large scale ground experiments, called very long baseline atom interferometers, in Wuhan, Hannover and in particular in Stanford, but also for experiments in the drop tower or parabolic flight campaigns.

It is intriguing to speculate about the ultimate potential of matter waves in fundamental physics. It is recognized that space represents for many matter wave tests a unique environment to exploit their potential, for example due to potentially long free fall time. For that reason, it is challenging to extrapolate the performance from ground-based experiments to the space-based ones. A freely falling laboratory is able to provide unique experimental conditions, necessary to exploit the ultimate limits of quantum sensors and push the measurements' accuracy to levels not accessible on ground. Space offers:

- Infinitely long "free fall" durations;
- Large variations of the gravitational potential;
- Large velocity and velocity variation;
- Long interaction times.

1.3.3. Atom Interferometers on ground vs in space: Recent and expected developments in the next ten years

Atom interferometers have made tremendous progress in the recent past both in the sources and methods for matter waves as well as demonstration activities on ground and in microgravity:

- The first dual species quantum test based on K/Rb has been performed on ground and several other experiments are on the way to be set-up to perform comparisons.
- Large scale experiments with extended free fall are in construction in Canberra, Hannover, Stanford, Wuhan, Florence, and Bordeaux.
- A matter wave interferometer was operated over 2.3 seconds of free fall in a large fountain. The device demonstrated that interferometers with an intrinsic precision of 10^{-13} per shot will become reality.

- A chip gravimeter was demonstrated and is a first spin-off from microgravity research.
- New interferometry concepts were proposed, which promise a further advancement in sensitivity or a relaxation of requirements.
- Interferometry with laser cooled atoms achieves a sensitivity below 10^{-10} of the local gravitational acceleration by integration and displays an accuracy of gravity measurement in the 10^{-9} range.
- Cold atom gravimeters have now become commercial products. Based on robust and turn-key technology, they are used both in the lab and in harsh environments for field campaigns.
- The first dual-species source atom interferometer as well as preliminary test of the Weak Equivalence Principle in weightlessness has been demonstrated on parabolic flights (ICE experiment).
- High flux BEC (Bose-Einstein condensates) sources and BEC interferometers were demonstrated in microgravity (Bremen catapult).
- US and German scientists cooperate to perform experiments in the NASA's Cold Atom Laboratory (CAL) planned to operate at the ISS 2016/17.
- New projects emerge for matter wave interferometers to reach the sensitivity required for the detection of gravitational waves.

Within the next years, experiments in parabolic flights, drop tower, and catapult will be continued and several sounding rocket campaigns will attempt to close the technology readiness gap of key ingredients for Q-WEP (Quantum Weak Equivalence Principle test) and STE-QUEST (Space-Time Explorer and Quantum Equivalence Principle Space Test). Depending on the success of the campaigns, an experiment such as Q-WEP might come in reach from 2020 on.

1.3.4. Atom Interferometry in Space

Quantum test of the Einstein principle of equivalence

Q-WEP on the ISS and STE-QUEST on a satellite are two mission scenarios for approaching an Eötvös ratio up to a few parts in 10^{15}. They are both based on an atom interferometer, where the propagation of matter waves within gravity can be observed in truly free-fall conditions over macroscopic time scales of tens of seconds. The information is stored in the phase of two waves accumulated while propagating along different geodesics and read out at the end of the interferometer.

Testing the foundations of quantum mechanics

The high sensitivity of atom interferometry instruments in space would also open interesting perspectives for testing the foundations of quantum mechanics: linearity, superposition principle, search for fundamental decoherence, test of dispersion relation or search for nonlocalities (in the sense of higher derivatives in the Schrödinger equation, for example).

Gravitational wave detection

Since a few years, matter wave interferometers are also studied and promoted as candidates for future gravitational wave detectors in the deep infrasound range. A recent example is the cooperation of scientists from the US and Europe. Extrapolating STE-QUEST to the scenarios of ESA's Gravitational Observatory Advisory Team (GOAT) one might even hope for more stringent tests. Moreover, those experiments are setting also bounds to possible fundamental de-coherence mechanisms.

Satellite gravimetry

The interest of atom interferometry is not limited to fundamental physics. These techniques find interesting applications in satellite gravimetry, gravity gradiometry, and navigation. ESA is currently performing several studies in this respect to study for example a cold atom gradiometer. Under the Earth Science Technology programme of NASA, a transportable gravity gradiometer with the space operation design consideration and performance has been recently demonstrated.

Open fundamental scientific question	Focus of space experiment	Relevant research topic	Related recent and future space experiments	Comments on microgravity relevance
Equivalence Principle: Are matter waves propagating universally ?	Equal phase shift in matter wave interferometers	Gravitational acceleration in matter wave interferometers Coherence	Parabolic flight experiments with K/Rb (ICE) Drop tower experiments with K/Rb (QUANTUS) Q-WEP - Test on board of the ISS STE-QUEST satellite mission Matter wave tests complemented by MICROSCOPE performing classical EP tests	Extended free fall Gravity acts as centripetal force Large variation of gravity Verification mechanisms Control of environment (inertial noise, rotations, etc.)
How long will coherence be preserved for large delocalisation?	Study of delta kick collimation		Drop tower, Sounding rocket, large scale atomic fountains	
What coherence length can be achieved in space?			Drop tower, Sounding rocket	

Table 1.3: Fundamental questions to be studied by the mission Q-WEP on the ISS

Development of atom interferometers for space applications

The development of atom interferometers has been pursued on national level with the support of ESA and several space agencies, such as ASI, CNES, DLR and UKSA. In Italy, the Space Atom Interferometer (SAI) prototype is being further studied and used by G. Tino for realizing a portable gravimeter. In France, the ICE project continuously evolves in developing a K/Rb dual species interferometer. Several parabolic flight campaigns have been successfully passed and the large challenge of the high vibrational noise is solved by implementing innovative methods for noise compensation and data extraction. Fibre lasers operating at telecom wavelengths have proven a rugged technology during these experiments.

In Germany, the QUANTUS (Quantengase Unter Schwerelosigkeit) cooperation is working on Bose-Einstein condensation as an ultra-cold source for interferometry in the drop tower and catapult. A high-flux BEC machine is demonstrated in extended free fall in the Bremen catapult. These experiments have now accumulated a total time under microgravity of about one hour. A dual species apparatus is in construction for long-time interferometry in the Bremen catapult. Several sounding rocket missions will allow to touch on the parameters range accessible with the ISS or on satellites.

Also ESA started development campaigns for critical payload components especially related to satellite gravimetry such as atom chip devices or laser systems. Further development activities are on the horizon.

US scientists are currently funded by NASA to conduct collaborative research with European colleagues for the QWEP programme. In particular, NASA has recently sponsored a pre-phase A study of QTEST (an experiment for test of the Einstein equivalence principle, EEP, with dual species atom interferometers on ISS) which included both science and engineering feasibility studies and the flight payload concept design. A summary of it has been accepted for publication in the New Journal of Physics.

A set of recommendations

In the near term period 2016-2020

- ESA should study (phase A) the atom interferometry test of the Weak Equivalence Principle for a mission opportunity on the ISS (Q-WEP) or on a dedicated satellite (STE-QUEST) in the 2016-2017 timeframe.
- Ground based support for closing the technology gap has to be secured by ESA activities in the 2016-2019 timeframe, with the goal of establishing full feasibility of the mission.
- Financial support of Topical Teams should be enlarged to organize workshops.

In the medium term period 2020-2024

- The ISS should be maintained until 2024 and beyond. Indeed, the ISS is an important platform for experiments under microgravity conditions, especially for studying atom interferometry techniques.
- In coordination with national agencies, ESA should start a development programme (phase C and D) for the atom interferometry instrument, particularly focusing on the key components - the atom source, the vacuum and laser systems, etc. - to bring it to flight maturity, thus assuring that Q-WEP will be ready to be operated on the ISS from 2022 on.

1.4. Specific Objective C: Ultra-High Energy Research from Space

1.4.1. Introduction

The Extreme Universe Space Observatory (EUSO) is a mission to be hosted on-board the International Space Station. EUSO is being designed to search from space ultra-high energy (UHE) cosmic rays. These are charged particles with energies from a few 10^{19} eV to beyond 10^{20} eV, at the very end of the known energy spectrum of cosmic radiation. From the reconstruction of the nature of the UHE primary particle, of its energy and direction, EUSO aims at unveiling the sources of the most energetic events produced in nature, and therefore at explaining the mechanisms capable of accelerating these particle to their -difficult to explain- velocities. EUSO is also expected to discover predicted, but up to now not observed, UHE neutrinos, photons, and other exotic particles, providing therefore a unique opportunity to explore a largely unknown aspect of our Universe. In addition to its astro-physics science programme, EUSO will observe slower transient luminous events developing in the atmosphere such as meteors, meteoroids or a variety of atmospheric phenomena generating UV signatures (Elves, Sprites and more).

The mission, principally based on a wide-field-of-view (60 deg) near-UV telescope, with a diameter of 2.5 m, will monitor the Earth's atmosphere at night, pioneering the observation from space of the ultraviolet tracks (290-430 nm) associated with giant extensive air showers (EAS) produced by UHE primaries propagating in the Earth's atmosphere. Observing from an orbital altitude of ~400 km, the mission is expected to reach an instantaneous geometrical aperture of about $A_{geo} = 2 \times 10^5$ km^2 with an estimated duty cycle of about 20%. Such a geometrical aperture allows unprecedented exposures, significantly larger than what can be obtained with ground-based experiments. The UV telescope, pointing to nadir or almost nadir, records the EAS tracks with a time resolution of 2.5 μs and a spatial resolution of about 0.5 km (corresponding to 0.075 deg). These time-segmented images allow determining the energy and direction of the primary particles.

The main UV telescope will be assisted by a LIDAR (Light Detection And Ranging) and an Infrared camera to monitor the atmospheric scenes in which the events are developing. Being hosted onboard the ISS, EUSO orbits the Earth every ~90 minutes.

1.4.2. Updating the EUSO Science Case

Searching for ultra-high energy cosmic rays

The specific questions for this topic are indicated with A in Table 1.4.

The main objective of EUSO is to begin the new field of particle astronomy and astrophysics by identifying the sources of UHE cosmic rays (UHECRs). The study of UHECRs, from 1 to about 60 EeV, has progressed considerably over the last decade due to observations by giant ground arrays culminating with the 3000 km^2 Auger Observatory in Mendoza, Argentina, the largest observatory worldwide, and the 700 km^2 Telescope Array (TA) in Utah, USA, the largest in the northern hemisphere. These two leading observatories have made precise measurements of the spectrum over a wide range of energy, each in their own hemispheres. Both experiments observe a suppression of the spectrum at the highest energies. Whether this suppression is due to the GZK effect predicted by Greisen, Zatsepin, and Kuzmin[1] or to the maximum energy reached by accelerators is still matter for EUSO to explain.

The mysterious sources of UHE cosmic rays most certainly involve extreme physical processes in extreme extragalactic environments as very few known astrophysical objects can reach the requirements imposed by the observed spectrum, composition, and lack of strong anisotropies. In particular, the lack of anisotropies towards the Galactic plane implies an extragalactic origin for protons above ~ 1 EeV and above ~ Z EeV for nuclei with charge Z.

1 According to the GZK effect ultra-high energy protons interacting with the cosmic microwave background (CMB) lose energy through photo-pion production and heavier nuclei photo-dissociate by interacting with cosmic backgrounds (from microwave to ultraviolet).

As they traverse cosmological distances, UHE cosmic rays lose energy through interactions with cosmic photon backgrounds (GZK effect) limiting the observable horizon for protons and iron nuclei to about 100 Mpc for energies above 60 EeV. Therefore, the volume of the Universe sampled by UHE cosmic rays, regardless of their composition, is local in cosmological terms and encompasses a region where the large scale matter distribution is inhomogeneous. The possibility of observing many events from the nearest sources and the anisotropic distribution of sources within a few 100 Mpc is what drives the need to increase significantly the statistics above 60 EeV, an energy range usually referred to as extreme energy (EE). This is the key goal of EUSO. Hints of anisotropies in the sky distribution of events above around 60 EeV have been reported by Auger and most recently by TA. The TA collaboration published the suggestion of a hotspot of about 20 deg in the sky, where 19 events above 57 EeV accumulated over 5 years, instead of the expected 4.5. These interesting findings may signal the first source of UHECRs to be located. A 5 year EUSO mission will collect a few hundreds of events from the TA Hotspot and a total of about 2200 events above 57 EeV (based on the UHE cosmic ray flux normalisation suggested by TA). This significant increase in statistics will sharpen the EE cosmic ray image of the TA hotspot allowing for a multi-messenger campaign to identify the nature of the first UHE cosmic ray source. In addition, the increase in statistics by EUSO will be over the complete sky which enables the identification of other regions of higher flux from the direction of other sources.

In terms of UHE cosmic rays composition, Auger observes a trend towards heavier nuclei at the highest energies starting above about 5 EeV. This trend can also indicate a change in hadronic interactions at the extreme interaction energies. TA reports a "proton" dominated spectrum throughout their sensitivity range and the data between the two experiments is consistent within errors. Identifying the sources with EUSO can help in determining the composition with studies of source shape distortions at the highest energies. In addition, the two-orders-of-magnitude increase in fluorescence data from EUSO will enable good determination of the shower maximum for a good fraction of the events, helping to determine the composition above 60 EeV.

Thanks to the all sky survey, EUSO will access the study of large scale multipoles, such as dipoles and quadrupoles, which are challenging for observations with partial sky coverage. In addition, discrepancies between the spectra reported by Auger and TA can be settled by EUSO. This spectral difference may be due to different systematics in energy or exposure determinations or to a real difference in the flux between northern and southern hemisphere. EUSO will be able to observe with the same instrument both hemispheres and with increased sensitivity at the highest energies. This will settle the question of the difference in spectra and the possibility of a spectral recovery at the highest energies.

Exploratory objectives.

The specific questions are reported in Table 1.5.

In addition to studying the highest energy cosmic rays, EUSO is also capable of observing extreme energy cosmic photons and neutrinos. The propagation of extreme energy cosmic rays through the cosmic background radiation produces extreme energy gamma-rays (EEGRs) and neutrinos (EEνs) as a natural consequence of π^0 and charged π production respectively (often called cosmogenic photons and neutrinos). EUSO will search for EEGRs and place stronger constraints on their flux. A detection of a higher than expected flux can be due to a new production mechanism, such as top-down decay or annihilation, or beyond standard model effects like the breaking of Lorentz Invariance.

An example of top-down models is the idea that the dark matter may be produced through gravitational processes around the inflationary epoch of the early universe. Or, around the grand unification theory (GUT) scale, super-heavy dark matter (SHDM) particles are long lived and the best way to constrain their lifetime is through UHE observations. It has been recently discussed that super-heavy dark matter can be discovered by a precise measurement of CMB tensor modes combined with high statistics measurements of cosmic rays above the GZK cut-off. EUSO will have unprecedented sensitivity to these models.

The detection of extreme energy neutrinos, EEνs, is another exploratory objective of the EUSO mission. The flux of cosmogenic neutrinos around 100 EeV is highly dependent on the maximal energy of UHE cosmic ray sources. For high enough E_{max}, a flux of “cosmogenic” neutrinos is within reach of the EUSO mission. Apart from the diffuse “cosmogenic” neutrino flux, a neutrino flux from isolated extremely energetic sources may also be observed by EUSO. The acceptance for EEv events is well above current detectors. In addition, earth-skimming events transiting ocean result in an order of magnitude larger acceptance compared to those transiting land. Since ground-based observatories cannot observe ocean events, only space-based missions can realize the advantage of this possible enhancement of the acceptance over the ocean.

EUSO will also monitor the earth’s dark atmosphere to observe atmospheric transient light events and meteors. Meteor observations by EUSO will help derive the inventory and physical characterization of the population of small solar system bodies orbiting in the vicinity of the Earth. EUSO may become the first space-based platform to monitor meteor events, which are eminently “slow” when compared to UHECR showers.

The observing strategy developed for EUSO to detect atmospheric and meteor events will also be sensitive to other hypothetical slow velocity events such as nuclearites or massive strangelets (quark nuggets with a fraction of strange quarks similar to up and down quarks). EUSO is sensitive to nuclearites with mass $m > 10^{22}$ GeV/c^2. A null observation of these events will set strong constraints on their flux, reaching one order of magnitude more stringent limits than current ones in only one day of observations. This search is a great example of the multi-disciplinary capabilities of the EUSO mission.

1.4.3. Why from Space

The most relevant advantage of space-based observations of UHE cosmic rays is the extremely large area that can be monitored from space. The instantaneous observational area of $A_{geo} = 2 \times 10^5$ km^2 (in nadir mode) implies a target air mass of more than 10^{12} ton, and can reach about 7×10^5 km^2 when the telescope axis is tilted with respect to the nadir. These figures are almost two orders of magnitude larger than those of the largest ground based observatories.

A second relevant feature of the space-based approach to the observation of UHE cosmic rays is the highly uniform exposure over the full sky. EUSO, and UHE cosmic rays space observatories in general, naturally provide a 4π sky coverage, in contrast to ground-based observatories that can observe only the southern or northern hemispheres. The highly uniform exposure of EUSO, is essential to minimise systematics in the statistical analysis studies of arrival directions, needed to understand the anisotropy of UHE cosmic rays at various scales.

Another advantage is the large and well-constrained distance between the instrument and the location of the EASs. EASs are in fact constrained to a track length of 10-20 km, rather small compared with the height (about 400 km) of the ISS orbit.

In addition, space-based observatories have the possibility of observing in cloudy conditions since, in most cases, the maximum of the shower occurs above the cloud-top. Assuming a duty cycle of about 20%, the currently expected trigger efficiencies, and an operation time of about five years, EUSO can reach an annual exposure close to an order of magnitude larger than the currently operating ground-based observatories.

1.4.4. Recent Progress and Status

EUSO is being designed by a large international collaboration. The JEM-EUSO collaboration[2] currently includes more than 300 scientists from 90 participating institutes, in 16 countries. Participating countries are: USA, Russia, Japan, Mexico, Algeria and Korea, and, from Europe, Bulgaria, France, Germany, Italy, Poland, Romania, Slovakia, Spain, Switzerland and Sweden.

The last years have been characterized by intense analytical, simulation and experimental studies of the scientific, observational and technological aspects of the mission. These studies are well summarised in the special issue of the

2 The international collaboration developing the EUSO mission still keeps the names of JEM-EUSO. The name goes back to when the JEM-EUSO mission to be hosted on the ISS JEM module was actively studied by JAXA. We wish to observe that the JEM is still an excellent option to host EUSO.

Experimental Astronomy Journal devoted to EUSO and recently published: Experimental Astronomy, Special Issue on JEM-EUSO Mission, Volume 40, Issue 1, November 2015. This is available at: http://link.springer.com/journal/10686/40/1/page/1

A similar effort is also summarised in the more than 45 contributions to the recent International Cosmic Ray Conference 2015 in The Hague (The Netherlands).

In parallel to the studies for the main EUSO mission, two pathfinders have been developed in the last years by the JEM-EUSO collaboration: the EUSO-Balloon and EUSO-TA.

EUSO-TA is a ground based observatory that consists of a prototype module of the main mission. It is made of a Photo-detector module, containing 36 Multi-Anode photomultiplier tubes, placed at the focal plane of a refractive optics consisting of two Fresnel lenses. EUSO-TA has been developed to test "on-ground" the EUSO observational technique as well as its basic technology. EUSO-TA has been deployed in 2014 at the site of the TA observatory in Utah, in collaboration with the ICRR, the Institute for Cosmic Ray Research in Tokyo and the TA collaboration. It is taking data for cross-calibration tests, background observations and, is being operated in conjunction with the Electron Light Source and the Central Laser Facility at the Telescope Array site, and with the portable laser facility of the Colorado School of Mines. At the time of writing, EUSO-TA has already properly detected artificial EAS tracks simulated with the portable laser system from the Colorado School of Mines and has detected its first cosmic ray events.

The EUSO-Balloon has been conceived as a pathfinder for the EUSO mission concept. The EUSO-Balloon has been developed by the JEM-EUSO collaboration as a demonstrator for the specific technologies and methods featured in the main mission. The mission is led by the balloon division of CNES, the French Space Agency. The instrument has been built by the collaboration. EUSO-Balloon is an imaging UV telescope, a scaled version of the EUSO telescope, pointing towards the nadir from an altitude of about 40 km. Using Fresnel Optics and a Photo-Detector Module, a prototype of the ones designed for the main mission, the instrument monitors a 12 deg x 12 deg wide field of view in the wavelength range between 290 and 430 nm, at a rate of 400,000 frames/s. The payload of the EUSO-Balloon also includes an Infrared Camera, a prototype of the one developed for the main mission. The first flight was launched on August 25, 2014, from the Timmins Stratospheric Balloon Base in Canada, in a balloon campaign led by CNES. The objectives of the EUSO-Balloon programme are threefold: a) perform a full end-to-end test of an EUSO prototype consisting of all the main subsystems of the space experiment; b) image the UV background originating from the Earth's surface, with spatial and temporal resolution relevant for EUSO; c) detect the tracks of ultraviolet light due to UHE cosmic rays for the first time from near space. The first flight has been indeed very successful. The background was measured under several conditions and although no cosmic ray tracks were detected, the instrument was able to detect artificial UV tracks induced by a laser beam shot from a helicopter flying in the field of view of the balloon. In addition we mention that the Infrared Camera performed according to the requirements and many maps of the observed scene were successfully taken and are being actively analysed. Given the success of the first flight, the EUSO-Balloon programme will continue with future flights.

1.4.5. EUSO in the ESA's Physical Science Roadmap

In the near term period 2016-2020

EUSO-Balloon

Given the success of the first flight the EUSO-Balloon programme is being continued. An opportunity to fly, under CNES leadership, over the ocean from Aire-sur-l'Adour, France, with an improved payload is under consideration for July 2016. This will allow the test of a second-generation payload, the tests of triggering technique, and the characterization of the ocean scene. The next major step of the balloon programme will be a long duration flight (tens of days) with a NASA Super Pressure Balloon (SPB), from Wanaka, New Zealand. The mission is led by NASA and the payload is being built by the JEM-EUSO collaboration. The key objective of the SPB flight is the first observations of UHE cosmic rays from a near space environment, using the fluorescence technique, at the core of the EUSO observational technique. The mission will also characterize slow-varying UV light and search for UV pulse like signatures from other objects: Meteoroids, Transient

Luminous Events (TLEs), Strange Quark Matter (SQM), Lightest Supersymmetric Particles (LSP). The second objective is the test of new technologies such as silicon photomultipliers (SiPMs) for the focal surface.

MINI-EUSO

The JEM-EUSO collaboration is also developing and currently building a new near-term pathfinder mission: MINI-EUSO. MINI-EUSO, already included in the ISS science programmes of Roscosmos and of the Italian Space Agency (ASI), consists of a small, compact UV telescope hosted inside the Russian Segment of the ISS, and placed in the nadir looking UV window of the module. The key objective of the mission is to characterize the UV earth background, and its variability, as seen from the ISS. In addition to measuring and monitoring the UV emission of night-time Earth, MINI-EUSO will provide a measurement of the expected duty cycle of the main mission. MINI-EUSO will study in addition a variety of UV atmospheric and bioluminescence phenomena. It will also observe several meteors. The start of onboard operation is scheduled for 2017.

ESA will support coordination with Roscosmos and at national level for the programmes presented above, which require relatively small amounts of funding.

EUSO

In the near term period we intend first to continue our efforts toward the completion of the design of the EUSO mission, a space observatory that allows a significant increase (from a factor of several to a factor of ten) in the annual exposure compared to those of the current generation ground-based UHE observatories. In the same period we intend to start, if possible, the actual implementation of the mission. A concrete occasion to develop such a mission is given by the current ongoing studies of the Russian KLYPVE mission, included in the "Long-term program of scientific applied research and experiments planned on the Russian segment of the ISS". As of 2015 KLYPVE is included in the "Stage program of scientific and applied research and experiments" and the technical requirements are officially approved by RSC "Energia". The "Stage program for 2016-2020" was recently (September 2015) discussed by the STAC committee and the KLYPVE mission has been approved. According to the current schedule, the conceptual design will be released in June 2016, while the delivery of the instrument to the RSC "Energia" company is foreseen in 2020. Operation of the instrument is foreseen after 2020. In its baseline version KLYPVE (commonly referred to as K-EUSO), uses a compound mirror concentrator, reaching a better efficiency but a smaller field of view, and uses a Fresnel corrector lens to significantly reduce the size of the reflected spot on the focal surface. In its advanced version KLYPVE can use Fresnel based refractor optics, increasing further the field of view of the mission to that of the EUSO mission. This last option requires a strong involvement of the European team and of ESA.

The role of ESA is in coordination and providing the European contribution to the mission whereas the science tem intends to explore the possibility of an ESA Mission of Opportunity participation to the mission in view of a collaborative efforts between the Human Spaceflight and Robotic Exploration Directorate and the Science Directorate.

An alternative to the use of the ISS is the use of the Chinese Tiangong space station currently in development and expected to be completed in 2020. Preliminary contacts between European and Chinese scientists in view of a common project for the search of UHE cosmic rays have already been initiated.

In the medium term period 2020-2024

The key objective in the medium term period is to complete, launch and operate the EUSO (or any EUSO-like) mission. The extension of the mission to beyond 2024 will certainly facilitate the completion of the EUSO science programme.
In the following table we summarise the key science questions we intend to answer with our investigations, and the strategy to reach these answers. As the required studies need to rely on a wide spectrum of parameters (like the UV background or the duty cycle) we also include a set of preliminary questions on the characterization of these parameters.

Open Fundamental Science Question	Focus of space experiment	Related experiments in space or near space	Relevant research topic
A.1: What is the spectrum of Cosmic Radiation at UHE energies?	Significantly higher statistics than attainable with on-ground UHE observatories.	Operation of the EUSO mission for 3+2 years.	Investigate the end of the spectrum (GZK effect and/or maximum energy at source?) and its possible recovery.
A.2: Is the UHE CR spectrum the same for the northern and southern hemispheres?	Uniform exposure for both hemispheres.	Operation of the EUSO mission for 3+2 years	Effect of local sources on the cosmic radiation spectrum, composition and deflection patterns
A.3: What are the sources of the UHE Cosmic rays?	Significantly higher statistics than attainable from ground; Good angular resolution. The high statistics might allow the study of individual sources.	Operation of the EUSO mission for 3+2 years + multi-messenger studies	Identification of the UHECRs sources and of the acceleration mechanisms able to accelerate these particles. Study with high statistics of the TA hotspot, enabling multi-messenger observations.
A.4: Do we observe large scale anisotropies in the distribution of cosmic radiation?	High statistics combined with uniform exposure on both hemispheres.	Operation of the EUSO mission for 3+2 years.	Study of large scale anisotropies, notably dipolar and quadrupolar, which are ambiguous from observations with partial sky coverage.
A.5: What is the composition of cosmic radiation at the highest energies (above 60 EeV)?	High statistics and good determination of the maximum of the shower in terms of slant depth (X_max), above 60 EeV	Operation of the EUSO mission for 3+2 years.	Identification of the sources helps to determine the composition. The two orders of magnitude increase in fluorescence data from EUSO will enable good determination of the shower maximum for a good fraction of the events, helping to determine the composition above 60 EeV.

Table 1.4: key questions on the search for UHE cosmic rays.

Open Fundamental Science Question	Focus of space experiment	Related experiments in space or near space	Relevant research topic
B.1: What is the flux of neutrinos at the UHE?	Very high exposures for neutrino detection. Solid discrimination of neutrino-induced events. Larger acceptance for Earth-skimming events transiting ocean (unattainable on ground).	Operation of the EUSO mission for 3+2 years.	Test flux, or limits on the flux, on the neutrinos expected at UHE from cosmogenic, astrophysics or top- down mechanisms. Study of the neutrino cross sections at extreme energies.
B.2: What is the flux of UHE photons?	Very high exposures for photon detection. Solid discrimination of photon-induced events	Operation of the EUSO mission for 3+2 years	Test or set strong limits on the photon flux at extreme energies. A detection of a higher than expected flux can point to a new production mechanism such as top-down decay or annihilation or the breaking of Lorentz Invariance.
B.3: What do we learn from fine timing UV observations of atmospheric phenomena?	Wide Field of view observations of the earth at night time in the UV and with fine time resolution.	Operation of the EUSO mission.	Observations of a variety of atmospheric phenomena like Sprites, Elves and other transient light events.
B.4: What do we learn from fine timing UV observation of slow UV events propagating in Earth's atmosphere?	Wide Field of view observations of the Earth at night time in the UV and with fine time resolution.	Operation of the EUSO	Study of meteors and of other hypothetical slow velocity events such as nuclearites or massive strangelets.

Table 1.5: key questions of the exploratory objectives.

Open Question	Focus of space experiment	Related experiments in space or near space	Relevant research topic
C.1: What is the UV background over the ocean?	Observation of the UV background and its variability over the ocean.	EUSO-Balloon flight from Aire-sur-l'Adour	Test improved technology of the mission, characterize the background and its variability.
C.2: Observation of Cosmic ray events from near space	Long duration flight from near space to test the technology and the observational technique of the EUSO mission	EUSO-SPB long duration flight	Triggering and detection of cosmic ray events from near space conditions. Monitoring of the UV background and its variability. Observation of slow varying UV events.
C.3: Characterization of the EUSO observational technique and its main parameters from the ISS.	Operation of an EUSO scaled down prototype from the ISS.	Operation of the MINI-EUSO mission.	Observation of the UV background and its variability from the ISS. Study of the mission duty cycle. Study of various UV phenomena occurring in the atmosphere.
C.4: Test of advanced EUSO technology	Operation of advanced prototypes of instrument elements	EUSO-SPB long duration flight, MINI-EUSO mission.	Tests of advanced technology like SiPMs detectors, and new concept digital electronics

Table 1.6: Questions associated to the near-term pathfinder programme.

ROADMAP 2: A ROADMAP FOR SOFT OR COMPLEX MATTER RESEARCH IN SPACE

2.1. General Introduction

Soft condensed matter represents a very large class of materials whose properties have in common the feature that they are easily deformed. The interactions between the phases that often constitute soft matter can be very much richer than found among atoms or molecules. Also, the interactions are often tuneable to a larger degree than possible in molecular systems. As the particles in soft-matter systems are much larger than atoms, soft matter is more susceptible to the effects of gravity. Typical examples of gravity effects are sedimentation of the constituent particles and gradients across samples. Similarly, the larger size of soft-matter particles entails a bigger impact of nonlinear effects and many situations out of equilibrium.

Soft matter under the present topic comprises the following very diverse systems: macromolecules, colloidal suspensions, complex plasma, planetary dust, foams, emulsions, and granular matter. While the list is roughly ordered by particle size, the regimes are not mutually exclusive. Similar physics is often found on quite a range of length scales, and similar diagnostic methods, e.g. light scattering or direct imaging, can be utilized in the measurements. Hence, synergies can be obtained among those diverse topics both regarding the ruling physics as well as the experimental methods.

In addition to their importance in fundamental research, soft matter systems are highly relevant in many fields of application and industry. In applications typically many different processes influence the behaviour of soft matter, so disentangling these processes is vital but most often not easy. Many of those processes can be investigated and understood best in the exceptional environment of weightlessness.

Pierre Gilles de Gennes, Nobel Laureate in Physics, defined soft matter as the matter able to deform under the action of small forces. By small forces, he meant forces corresponding to energies of kT, k being the Boltzmann constant and T the absolute temperature. As a consequence, the modelling of the behaviour of soft matter relies heavily on statistical physics tools and universal behaviour is frequently found in *a priori* very different systems. This is the case for the systems grouped in the present roadmap: foams, emulsions, granular media including dusty plasmas, colloids and proteins.

Following directly from the definition, soft matter systems have similar mechanical responses. Dense systems are solid, but melt easily under the application of a shear deformation. The variation with applied strain of the elastic modulus is similar, even up to melting for foams, emulsions and colloids. The dissipation, characterized by a loss modulus, is also similar. Both elastic and loss modulus describe what is called “rheological” behaviour, which is the object of many studies in these systems. Other similarities were found in the non-linear responses to shear stress: wet granular media change their composition, water is sucked in the regimes where the shear stress is larger; this is the well known behaviour of “quick sand” and it was also evidenced in systems as different as foams. Melting can only be produced by decreasing the volume fraction of objects (Φ) and the “jamming” fraction Φ^* is approached. It is not yet clear if jamming and solidification occur at the same f. When the solid is amorphous, the solidification process is a glass transition, and studied as such with colloids and proteins. The case of foams and emulsions is somewhat different because the objects are able to deform and the volume fraction can increase up to almost 100%. The behaviour around the “jamming” of all the systems will be studied and it is expected to be similar, at least in the region $\Phi<\Phi^*$.

Another important question is when the solid phase is going to be crystalline or amorphous (in the case of monodisperse objects). There are now some indications from proteins and colloids studies that the answer is linked to the interactions between objects: attractive or repulsive interactions can result in large differences in behaviour. The study of the large variety of the systems of the roadmap will bring many results and their comparison will certainly help to significantly advance our knowledge and understanding of this question.

A common property of the systems of the roadmap is that they are out of equilibrium and subject to ageing. 'Ageing' is the generic term to represent the slow internal evolution of the many internal degrees of freedom of the system. It leads to some unexpected consequences, such as "shear rejuvenation". Note that the rejuvenation is limited in the case of foams and emulsions, because of the intrinsic coarsening with time due to transfer of matter between objects because of differences in internal pressures. Understanding the similarities and differences of ageing in the systems under study will be a great achievement.

In order to clarify all these important issues, the need of microgravity is mandatory. This is quite obvious for large objects such as grains and foam bubbles. But even for smaller objects, large aggregates can be formed during solidification. In the solid phase, density gradients can be induced by gravity and change local interactions between objects.
Synergies can be identified once universal properties and generic behaviour in soft matter is considered. Across the individual soft-matter systems, several challenges stand out:

- **Jamming**, i.e., arrest in a mechanically stable state which is typically assumed disordered in structure. Jamming addresses primarily systems out of thermal equilibrium but may also be extended to thermal systems that show glassy arrest. Microgravity allows access to jammed as well as non-jammed states that are not accessible on ground. In addition, microgravity enables closer approach to the transition between jammed and unjammed states which should reveal critical properties of that transition. An improved understanding of jamming and disordered arrest in general forms the basis for the rheology in such soft-matter systems which is in turn of basic importance for processes in applications.
- **Structure formation and agglomeration** effects in non-equilibrium. Systems far from equilibrium allow for a range of pattern formation phenomena unknown to thermal fluids in equilibrium. Dust agglomeration, granular clustering, bubble agglomeration and aggregation in colloids are another phenomenon that hints at universal physics beyond the properties of individual experimental realisations.
- **Tailoring of interactions**. Characteristic to most soft-matter systems is the capability to change the relevant particle interactions of the constituent particles over a wide range. This possibility has been and will be a stimulating factor for theory in using soft matter within model systems to investigate and test novel correlated systems, which one cannot produce with molecular interactions. In turn, the emergence of novel and at times even innovative macroscopic behaviour in soft matter can be achieved by changing the interactions on the microscopic scale of the particle-particle interactions. In both laboratory and microgravity, this feature allows for the investigation, understanding, and productive utilization of all the soft-matter systems.

2.2. Introduction of the Different Topics

2.2.1. Physics of Foams

Foams are dispersions of gas in liquid or solid matrices. Industrial applications necessitate liquid (or solid) volume fractions f around 50%

When Φ is above the jamming limit of 36%, the bubbles are spherical, and foams are called bubbly liquids. To stabilise very wet foams, the continuous phase needs to be solidified. The continuous phase is liquid during foam production. In case it is solidified afterwards one arrives at a solid foam. Our knowledge on the wet liquid foams is very limited due to the impossibility to study these foams on Earth: the foams rapidly dry due to gravity drainage (Φ smaller than a few percent).

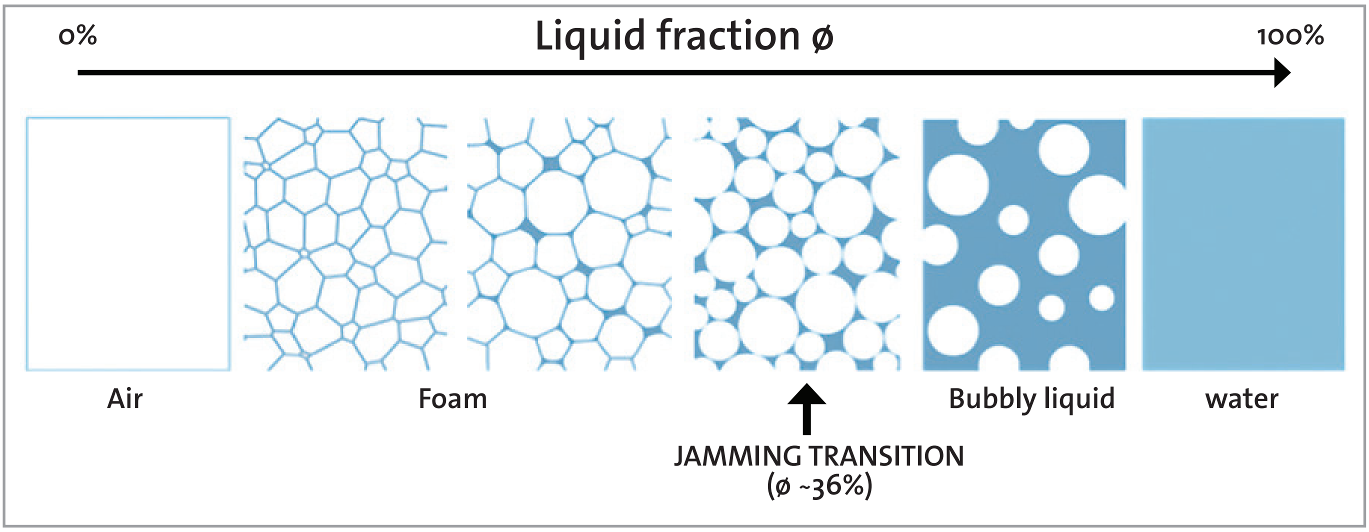

Figure 2.1: foam physical characteristics at increasing liquid fraction

Solid foams can be made with polymers, silica, metals, etc. They are used for catalysis, thermal and sound insulation, scaffolds for drug delivery and tissue engineering, manufacture of light containers and seating furniture, and to obtain light and resistant materials (metallic foams in car and space industries for instance). Solid food foams include bread, cakes, and meringue among others.

Organic liquids lead to more unstable foams which are mainly studied with view of how to avoid them, because they can be damaging (in motor oils for instance). Aqueous foams are widely used, for instance in detergency, food, cosmetics, fire-fighting (as barriers to oxygen), oil recovery (to exert pressure on the trapped oil) or flotation of minerals (bubbles behaving as carriers).

There are many open problems in foam science (presented in 2.3. Scientific Questions on Different Topics), common with emulsion science.

- Foaming: how to control bubble size and polydispersity? How to make large quantities of monodisperse foams? How to make nanosized bubbles? How to reduce process energy input?
- Foam geometry: how to describe the wet foam structure? Does it depend on the stabilizing agent?
- Wave propagation in foams: How does light travel through a foam?
- Can liquid foams be used as self-assembled precursors of solid meta-materials with useful mechanical, optical, acoustic properties?
- Self-organization of the packing structure and flow-induced ordering in wet foams. Can flow induced ordering in

monodispersed foams be used to create materials like photonic or phononic crystals?

- Foam rheology: What are the parameters describing the structure reorganization events? Is the duration of these rearrangements governing the constitutive rheological law as in granular suspensions or soft pastes ? How and why does solid-like behaviour appear at the jamming transition? How does foam yield in response to an increasing stress close to the transition. Do length and time scales of mechanical relaxations diverge at this transition, as predicted by jamming theories?
- Foam drainage: How to describe wet foams drainage? (only the dry foam case is understood)
- Foam coarsening (as transfer between bubbles): only understood for 2D dry foams. How to understand/characterize foam coarsening under shear and compression?
- Foam collapse and bubble coalescence: Mostly not understood
- Antifoam or defoaming action: Some understanding

2.2.2. Physics of Emulsions

Emulsions are fine (micrometric) dispersions of immiscible fluids - for example, water and an oily phase – characteristic of a vast number of natural and artificial products and which also find applications in different technologies and processes. In the most simple case, an emulsion is constituted by micrometric droplets of a first liquid dispersed into a matrix of another liquid.

Alike foams, emulsions are thermodynamically unstable systems which tend to separate spontaneously under the effect of different ageing processes. In particular after aggregation and coalescence, droplets increase their size and the separation is accelerated by the gravitational segregation.

Obtaining stable emulsions or, vice versa, being able to separate naturally highly stable emulsions is the most important issue concerned with emulsion technology. Emulsion stability is the consequence of the segregation of surface-active species (surfactant molecules, polymers, proteins, nanoparticles) at the droplet interface, which hinders the initial processes of aging, in particular, droplet aggregation and coalescence. These species, in fact, affects the equilibrium and dynamic behaviour of the liquid films between approaching droplets, which is in fact one of the most important elements concerned with emulsion stability.

While we currently have a general comprehension of the role of surfactants in emulsion stabilisation, the formulation of emulsifiers or de-emulsifier products is still rather empiric. Emulsion stability is in fact the result of a hierarchy of different interconnected chemico-physical phenomena and dynamic processes developing on different scales, from molecular (adsorption of molecules at the liquid-liquid interface) to macroscopic (emulsion droplets' dynamics) passing through the mesoscale (dynamic behaviour of the liquid film between droplets). Therefore, at the current state-of-the-art it is still not possible to predict accurately the stability of emulsions from the knowledge of the chemico-physical properties of its constituents.

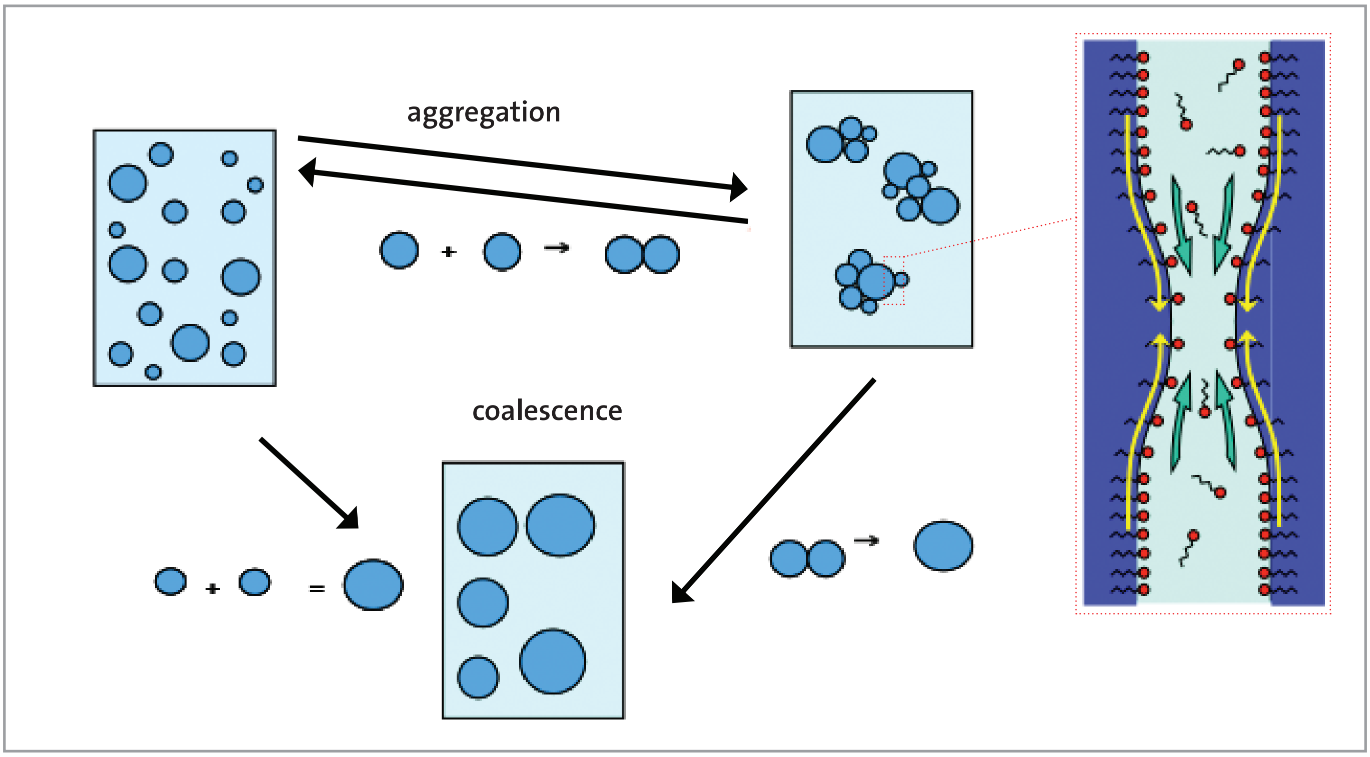

Figure 2.2: A hierarchy of multiscale dynamic processes is involved in emulsions aging.

Owing to the absence of buoyancy, microgravity conditions offer the unique opportunity to investigate the processes of destabilisation under the sole effect of the basic processes of aggregation, coalescence and coarsening. On the other side, it also offers the possibility to investigate the adsorption of surfactants at the single droplet interface and the behaviour of liquid films under the simplified effect of capillary-driven flows and molecular diffusion.

Such considerations inspired different microgravity-related studies for emulsions and adsorption dynamics in the last years, in particular based on the utilisation of facilities such as FASTER and FASES-EC, and constitute the motivation to continue such investigations using even more sophisticated experimental approaches, such as those offered by the SOFT MATTER DYNAMICS facility.

Because of the increasing availability of tailored nanoparticles, emulsions stabilised by associations of particles and surfactants are of rising interest in applications. These systems also offer important perspectives in relations to nanotechnologies, such as the development of new micro/nanostructured materials (e.g., solid foams, capsules, core-shell particles etc.), based on the processing of emulsions and foams. Studying these kind of emulsions under microgravity will benefit additionally from the absence of particle settling.

As illustrated in Table 2.2 (in section 2.3), the key question related to the physics of emulsions (and of foams) concerns:

- the prediction of the features (in particular the structure, the stability and dynamic/rheological behaviour) of emulsions based on the knowledge of the interfacial properties of the related liquid/surfactant solutions and liquid-liquid film.

Achieving such a target requires the investigation and modelling of the following items:

- The dynamic behaviour of liquid films in response to external mechanical stimuli.
- The structure and the dynamic behaviour of liquid films containing particles.
- How the single process of droplet coalescence and aggregation are related to the equilibrium and dynamic features of the concerned liquid films.
- How the presence of particles in the liquid film affects the above process (and droplet coarsening).
- Non-Brownian regimes in the dynamics of emulsion droplets.

Other questions related to the practical utilisation of emulsions (and foams) in chemical and material processing and, because of the absence of buoyancy, can benefit from microgravity investigation concern:

- The self-organisation of particles in liquid films.
- Heat and mass transport in emulsions.

Scientific questions related to emulsion physics that are proposed to be addressed are listed in Table 2.2 (in section 2.3).

2.2.3. Physics of Granular Matter

The scientists of the Space Grains Topical Team (www.spacegrains.org) aim to study the dynamic and static properties of granular media in a low-gravity environment, from dilute to dense regimes. In order to perform experiments, they participate in the conception and development of the VIP-Gran instrument in which grains are only driven by oscillating walls.

Granular systems are recognized to belong to a particular class of materials on Earth since grains may exhibit solid, fluid or gaseous behaviours. Although nearly 80% of the products manipulated in industries are powders and grains, many fundamental questions concerning their rheology are still unsolved. Space exploration (such as asteroid soil structures, powder propellants of rockets or planetary rings dynamics) and space exploitation (such as asteroid mining) will face major challenges concerning the handling of granular materials in low gravity environments. As an example, nobody knows how to perform a simple operation like sieving in space. Therefore, it is of primary interest to better understand the rheology, flow and dynamics of granular media in low gravity conditions.

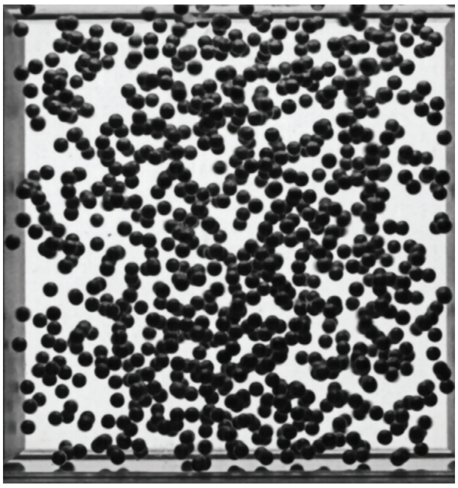

Figure 2.3: Gaseous regime in low gravity – 3D cell

The objective of the Space Grains TT is to perform unique measurements on granular gas, convection, segregation and jamming in granular materials subjected to vibrations without the symmetry breaking influence of gravity.

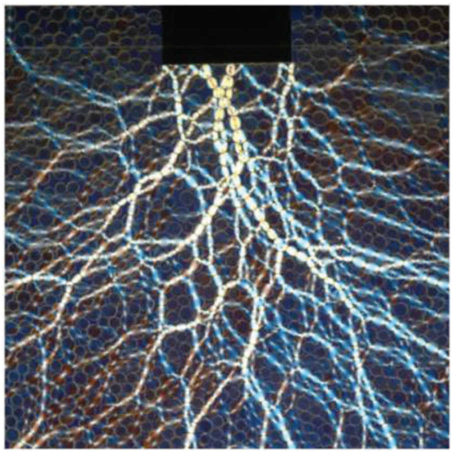

Figure 2.4: Force chains inside a two-dimensional granular sample shown by stress-birefringence. A three-dimensional version of the experiment allows the determination of forces across the jamming transition in microgravity.

The VIP-Gran instrument has been designed for that purpose: grains are inserted in a closed cell having two opposite moving walls, injecting periodically mechanical energy. Beyond the space exploration relevance, the motivation for low gravity is to achieve an experimental situation in which inelastic collisions between particles are the only interaction mechanism. The only time scale for such a granular system in low gravity is the period of wall oscillations that thus strongly simplifies the modelling of the system by using simple dimensional analysis. Moreover, dynamics is strongly affected by the constant gravity force for dilute regimes. In denser ones, the confinement pressure of grains due to their own weight, and the sedimentation strongly modifies the behaviour of granular matter. A level of low gravity is also required since g-jitters strongly influence the dynamics of the granular matter.

For dense granular matter, the topics of the jamming transition, i.e., the transition from a loose granular assembly to a force-carrying packing shall be addressed as well as sound transmission in granular packings and rheology. For granular packings, experiments in microgravity allow for the reduction in the gravitational pressure gradient caused by the weight of the granular particles. The granular packing in space can therefore be much more homogeneous and hence also allows closer approach to the transition. For detecting the transition in the emergence of permanent forces accurately, the method of stress-birefringence can be used which also promises insight into the transport properties of shock waves in the material.

Different experiments and experimental conditions are envisaged within the Space Grains project from the study of dilute systems to extremely dense assemblies. In order to rationalize the scientific objectives, four different goals were identified. Each goal involves specific types of cells, numbers and types of particles and protocols, as well as time scales. Each goal encompasses several fundamental questions that will be addressed such as:

- How does a granular gas (which is intrinsically dissipative due to inelastic collisions) deviate from the elastic limit of usual gas when dissipation increases?
- What is the phase diagram of dynamic states of such an out-of-equilibrium dissipative gas?
- What is the segregation mechanism in a granular composed of two types of particle species in low gravity?
- What is the large-scale dynamic of a dense granular medium mediated by a convection-like mechanism (when two walls vibrate with different velocities as a “thermal gradient”-like forcing)?
- What is the distribution of stresses inside a granular packing and how does a sound wave propagate in a granular packing without the confinement pressure of grains due to their own weight?
- In absence of gravity, the mechanisms of jamming within a granular flow (analogue to traffic jams on roads) or segregation between different particle species are unknown, and the relevant parameters that control convection are not yet identified. A detailed knowledge will provide new insights into the management of particles in Space.

The key scientific questions are detailed in Table 2.3 (in section 2.3).

The VIP-Gran instrument has been developed and a representative model was tested on parabolic flights. It demonstrated that the scientific requirements with the exchangeable cells type 2D and 3D are met.

Other cells have already been defined and developed and/or are at a detailed definition stage.

2.2.4. Physics of Complex (Dusty) Plasmas

Complex (or dusty) plasmas

These belong to the class of soft matter in which solid micro-particles (e.g. dust grains) are embedded in a low-temperature plasma. Complex plasmas are mostly produced by discharges in a noble gas (argon, neon) at low pressures (1 – 100 Pa) into which monodisperse micron-sized particles are injected. Due to electron collection these particles are highly charged (1000 – 10000 electron charges per micro-particle), leading to a strongly-coupled many-body system showing collective phenomena such as the formation of a plasma crystal (Figure 2.5). Since the particle system can easily be observed using laser illumination and cameras, complex plasmas are ideal model systems for studying the dynamic behaviour (e.g. phase transitions, self-organisation, non-equilibrium phenomena) of strongly-coupled many-body systems at the microscopic level. The aim of complex plasma research is the fundamental understanding of the physics of complex plasmas (particle-plasma and particle-particle interactions; macroscopic properties of the many-body system) and its application as model system for generic physical phenomena.

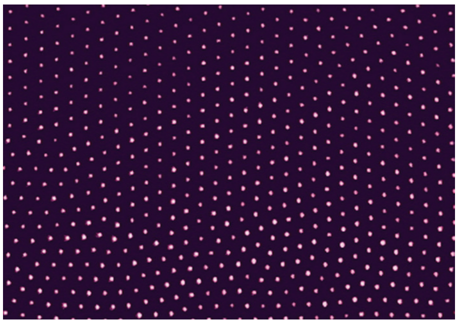

Figure 2.5: Top-view of a plasma crystal (Source: MPE)

The micro-particles can be levitated on ground only by electric fields in the so-called plasma sheath close to the bottom of the plasma chamber where they are strongly compressed and disturbed. An undisturbed investigation of complex plasmas is only possible under low gravity conditions. Therefore complex plasma experiments have been performed on parabolic flights, on sounding rockets and on board of orbital stations (MIR, ISS) since 1996. In particular, the experiment facilities PKE-Nefedov (2001 – 2005) and PK-3 Plus (2006 – 2013), which were constructed and operated successfully in cooperation between the Max-Planck-Institute for Extraterrestrial Physics (MPE) in Garching (Germany) and the Russian Academy of Sciences’ Joint Institute for High Temperatures (JIHT) in Moscow (Russia). This research yielded a large number of new and interesting results published in 67 articles in peer-reviewed journals.

The “PlasmaKristallExperiment-4”, PK-4, was developed in the ESA programme and launched to the ISS in October 2014 in cooperation with Roscosmos. During the development phase apparatus tests and scientific experiments were already performed on ground as well as on parabolic fight campaigns resulting in scientific publications. PK-4 is installed in the European Columbus Laboratory. Following a successful test and commissioning phase, first experiments were conducted in October 2015.

In contrast to its precursors on the ISS, in which radio-frequency discharges in compact plasma chambers were employed, PK-4 is based on a direct-current discharge in an elongated glass tube (Figure 2.6). This allows, in particular, detailed investigations of flow phenomena in the liquid phase of complex plasmas such as the transition from laminar to turbulent flow. A prominent example is the formation of an electro-rheological system (see Figure 2.7) simulating electro-rheological fluids used for technological applications, e.g. brakes or shock absorbers. Preliminary experiments have been undertaken during parabolic flights and results published in Physical Review Letters.

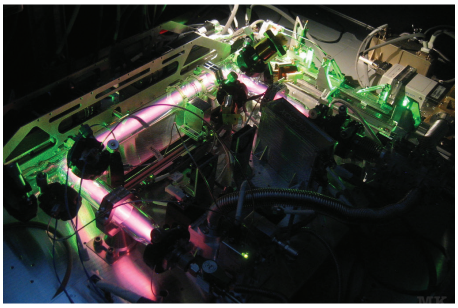

Figure 2.6: PK-4 during ground testing at MPE (credit: MPE)

The PK-4 set-up is equipped with various diagnostic tools and manipulation devices allowing a large variety of different experiments with complex plasmas similar to a laboratory facility. A list of key scientific questions to be addressed with PK-4 is presented in Table 2.4 (in section 2.3).

It is expected that PK-4 will be operated during two to four one-week long experiment campaigns every year until at least 2019.

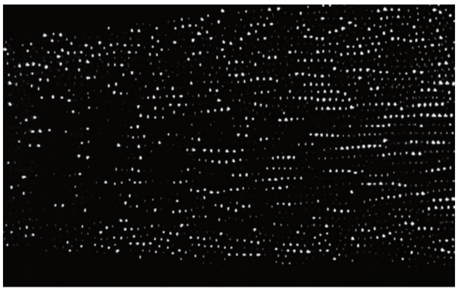

Figure 2.7: Formation of particle strings triggered by an external electric field as a model for electro-rheology (Source: PRL)

Further parabolic flight experiments are also planned to test, compare to, or improve ISS experiments, for example by using a faster camera for achieving a higher time resolution.

2.2.5. Interactions in Cosmic and Atmospheric Particle Systems (ICAPS)

Microscopic dust particles, often immersed in a gaseous medium, are ubiquitous in outer space and play an important role in a variety of cosmic and atmospheric environments. Nanometre- to micrometre-sized particles can be observed in different situations such as: stellar outflows; molecular clouds; proto-planetary discs; planetary atmospheres and in Earth’s atmosphere (where they determine the chemistry and temperature distribution and, thus, climate and weather of the planet); and cometary comae, tails and trails, the best source for pristine Solar-System material. In contrast to the much larger dust particles found on the surfaces of solid planetary bodies and in Saturn’s rings, small dust grains always experience considerable attractive van-der-Waals or hydrogen-bonding forces whenever they collide with each other. The presence of a gaseous environment generally damps the relative speeds so much that at least some of the inter-particle collisions can result in the sticking of the grains. The dust agglomerates so formed exhibit interesting morphological, mechanical, and optical properties. Systematic investigations of these quantities can help to understand the cosmic material cycle, the formation of the first solid bodies in the Solar System, the evolution of planetary atmospheres, and the cometary composition, activity and evolution at successive perihelion passages. In addition, future space missions to the Moon, Mars, or asteroids can benefit from knowledge about the physical interactions of small dust particles as taking place on regolith layers.

ICAPS aims at providing answers to the following questions:

- What is the nature of interplanetary and interstellar dust?
- What is the mass, structure and motion of small dust aggregates?
- How can we interpret the astronomical observations of light scattered by such dust?
- How did the planets form in the early Solar System?

More specifically, the scientific objectives of ICAPS are the study of dust-dust interactions, dust-gas interactions, dust-light interactions, dust-light-gas interactions.

The dust-dust interactions control the formation of dust aggregates. The resulting dust aggregates are characterized by a growth rate, a fractal structure and the distribution of their mass in a particle ensemble. All depends on the relative-velocity fields which are determined by the physical environment.

Changing the gas density and the effect of Brownian motion, i.e. the dust-gas interactions, will also affect the dynamics of the aggregates and eventually their growth and morphology. A transition from a gas-dominated to a dust-dominated two-phase flow is expected.

Most of the astrophysical clouds are only observed by the light they scatter under different phase (or scattering) angles and different wavelengths. Understanding dust-light interactions thus becomes a necessity to interpret observations. By analysing the light scattered by dust clouds whose composition, optical indices and evolving morphology indicate aggregation processes, one can establish a reference database. This requires measuring the angular distribution of the scattered light at different wavelengths as well as its polarized components.

The case of aerosols in Earth's atmosphere is even more complex because of the combination of dust-light-gas interactions. On top of the momentum transfer between the dust agglomerates and the ambient gas, light absorption and differential particle heating also influence the dynamics of the particles in the cloud (through photophoresis and thermophoresis).

What makes ICAPS particularly important is its capability to study, simultaneously, the dynamics and morphology of dust aggregation and the light scattering properties of the aggregates while they are being formed. This has not been done before.

The key scientific questions that are addressed in this roadmap for what concerns dust particles are listed in Table 2.5 (in section 2.3).

For a realistic simulation of cosmic aggregation processes, experiments must be performed under space conditions. Although many experiments have successfully been performed in short-duration free-fall (drop tower, parabolic flights), some fundamental aspects can only be revealed with experiments in long-duration low-gravity environments. These comprise the requirement of: ultra-low collision velocities among small protoplanetary dust particles in a low pressure gas environment (<1 cm/s for dust aggregates <1 mm in size in a minimum-mass solar nebula model), which can only be achieved for free-floating particles in a free-fall environment; the correspondingly long collision and aggregation timescales; the maintenance of a well-mixed particle ensemble comprising dust aggregates of different sizes and/or fractal dimensions, due to absence of sedimentation; and the extreme instability of macroscopic fractal aggregates against hydrostatic compression.

In the past years, extensive development work has been performed in the groups associated with ICAPS, which guarantees maximum scientific output concerning the fundamental questions outlined above. This comprises the definition and free-fall tests of a thermal dust-cloud manipulation system, which is capable of: compensating for external thermophoresis; of concentrating dust clouds against Brownian diffusion; of achieving high dust-to-gas ratios; as well as of manipulating individual dust aggregates for further optical or light-scattering inspection. Moreover, the definition of a sophisticated light-scattering unit has been finalised, augmented by numerous parabolic-flight campaigns with samples that can be investigated in short-duration free-fall. An extensive body of work has also been done in the field of dust-aggregate collisions and photophoretic motion of dust in rarefied-gas environments. ICAPS will build on these developments and will be an important step towards a deeper understanding of the physics of small dust and aerosol particles.

2.2.6. Physics of Colloidal Systems

Anomalous Dynamics in Colloidal Glasses

Scientific background.

Colloidal particles with repulsive interactions undergo a glass transition similar to that of molecular glass formers. While in a molecular system the control parameter is typically temperature, the colloidal glass transition is triggered by increasing the particle volume fraction Φ. Various theories describe the increase of the structural relaxation time τ_α with Φ. All of them predict the divergence of τ_α at some value Φ_g of the volume fraction.

Recent experiments challenge this scenario. In suspensions of soft particles, τ_α was found to increase sharply with Φ, as expected from theory, but eventually the system enters an anomalous regime where τ_α does not vary with volume fraction anymore and thus the dynamics is orders of magnitude faster than expected. In this anomalous regime, correlation functions decay steeper than exponentially, in contrast to the stretched exponential relaxations usually seen in glassy systems. Moreover, giant temporal fluctuations and extended spatial correlations of the dynamics are observed. Similar behaviours have been reported also for hard spheres and for nanoparticles in a polymer melt, for which the relaxation time exhibits an anomalous q^{-1} scaling with the scattering vector. Finally, these findings are likely to be relevant also for molecular glass formers, e.g. for metallic glasses, where XPCS experiments have recently shown faster-than-expected dynamics beyond the glass transition.

Space relevance

The onset of this anomalous dynamic regime generally coincides with the fluid-to-solid transition. Hence, one possible explanation is that these dynamics are due to gravitational stress that can propagate throughout a solid sample. Therefore, it is crucial to test this hypothesis by performing control experiments in space.

Specific Questions

- For dense suspensions of repulsive colloids in space, are anomalously fast relaxations observed? What is their dependence on the particle volume fraction and on the probed spatial scales?
- Can dynamical heterogeneities, namely, temporal fluctuations and spatial correlations of the dynamics, be detected?

Restructuring and Aging of Colloidal Gels

Scientific background

When the attractive forces induced by the presence of a high molecular weight additive acting as depletant become strong enough, a colloidal suspension undergoes a liquid—liquid (L-L) phase separation. As for simple liquid mixtures, a colloid suddenly brought within the L-L miscibility gap undergoes a spinodal decomposition process, consisting of phase separation followed by a progressive coarsening of the two phases. However, if the depletion forces are short-ranged, the spinodal decomposition usually gets arrested by the formation of a colloidal network, namely, of a disordered colloidal solid with a gel-like structure. Detailed investigations have shown that three distinct kinds of gels can be clearly set apart. When depletion forces are barely sufficient to drive the system within the metastable region, an initial disordered gel hosts the rapid nucleation of crystallites, which stress the gel structure until it fully collapses, leading to the formation of a macroscopic colloidal crystal (type 1 gels). For stronger attractive forces, two distinct scenarios are observed, depending on the particle volume fraction of the original suspension. At low Φ, the gel breaks after a short delay time into separate clusters that rapidly settle until they compact into a denser disordered phase (type 2 gels). For larger values of Φ , gel breaking is conversely suppressed and the structure undergoes a continuous compression that show strong analogies with syneresis in polymer gels, with microscopic dynamics resembling that of attractive colloidal glasses (type 3 gels). More recently, the survey has been consistently enlarged by controlling the strength of depletion forces with temperature, exploiting effects similar to those described in Table 2.6 (in section 2.3). In particular, very different crystal morphologies, ranging from dendritic to cellular structures, can be set apart.

Space relevance

While the collapse, the ageing, and even the microscopic dynamics of type 2 gels is fully ruled by the gravitation stress, the compression of type 3 gels shows an initial stage arguably due to an internal restructuring mechanism, which is unrelated to gravity. This mechanism would be the only one acting in space experiments, which would therefore allow to better highlight the similarity between dense colloidal gels and polymer networks. More generally, getting rid of the gravitational stress is the only way to investigate whether internal restructuring and ageing effects also take place for the tenuous gels generated by spinodal decomposition at low Φ, and to study crystal growth in a gel without stressing and eventually breaking the latter.

Specific Questions

- Does the depletion gel scenario highlighted by ground experiments drastically change in the absence of gravity?
- Can the existence of internal stress-relaxation mechanisms, suggested by the experimental evidence obtained on ground, be confirmed and better highlighted in space?

Self-Assembly of Patchy Colloidal Particles

Scientific background

In the past few years, novel techniques have allowed the assembly of colloidal particles decorated on their surface by a predefined number of attractive sticky spots, i.e., particles with specifically designed shapes and a number of interaction sites which plays the role of a "valency" v. While simple particles behave as "big atoms", these "patchy" colloids are rather suggestive of molecular fluids, and can be exploited to tailor novel colloidal superstructures, which can be controlled by tuning solvent properties. A promising approach is solubilizing the particles in a binary mixture displaying a critical point, using temperature as a control parameter. Recent ground experiments have shown that particles with $v = 2$ self-associate into polymer-likes structures with a variable stiffness that depends on the patch-to-patch binding strength, which can be tuned by exploiting the critical Casimir effect taking place close to the phase separation of the binary mixture. Further experiments with higher valency particles suggest that a wide variety of novel, complex structures can be obtained, opening the door to entirely new opportunities for structural design at the nano scale.

Space relevance

Knowledge about the growth principles and the best strategy to achieve complex colloidal structures by rational design is still limited. On ground, the growth of these structures is altered by gravity effects, generating particle settling and consistent stress on the aggregated structures. Hence genuine insight into the natural growth of these complex structures needs the space environment. In fact, a first series of experiments on colloidal aggregation in space (SODI-Colloid) on simple spherical colloids has shown that, by exploiting the critical Casimir effect, particles can be directed into non-equilibrium aggregates as well as dense equilibrium structures.

Specific Questions

- How does self-assembly of patchy particles depend on valency and interaction strength?
- How much flexibility and control of the self-assembled structures is actually gained by working in space, with respect to ground experiments?

Optothermal Manipulation of Colloidal Solids

Scientific background

Novel evidence about the structural and dynamic behaviour of colloidal solids and aggregates could be obtained by generating stresses associated with the presence of a thermal gradient. Rapid and spatially localized temperature jumps can be obtained by all-optical methods using a "pumping" beam which is partially absorbed by the sample, generating a spatially-varying temperature field. Several effects can originate from the presence of the induced temperature field. In a transient regime, for instance, the colloidal solid would be perturbed by the stresses associated with the local solvent expansion. If the power of the pumping beam is modulated at sufficiently high frequency, this cyclical perturbation would amount to a local annealing of the colloidal structure. Besides, structural perturbation will be present in stationary conditions too if the colloidal structure is subjected to effective "thermal forces" (akin to thermophoresis), or when the effective interactions at the origin of the structure depend on temperature. The effects of the thermal perturbation can be probed by a secondary beam, sent for instance collinearly with the pumping radiation.

Space relevance

In opto-thermal experiments like the one described, the induced temperature field necessarily has radial symmetry. Hence, in the presence of gravity, a horizontal thermal gradient, giving rise to convective motion, is unavoidably present. Therefore, space conditions are required whenever the experimental timescales for structural relaxations are sufficiently long for convective effects to be relevant. For aqueous samples, these opto-thermal pump-and-probe experiments can be performed in the Colloidal Solids scattering setup.

Specific Questions

- What are the annealing effects on a colloidal glass or gel due to a cyclical thermal stress?
- What are the structural perturbations induced at steady state by local heating on a colloidal structure where inter-particle interactions are temperature dependent?

More details of the scientific questions addressed in the field of colloid physics can be found in Table 2.6 (in section 2.3).

2.2.7. Physics of Macromolecules

Background

Protein structures are essential for understanding fundamental processes in biology, are pivotal to the success of rational drug design, and enable numerous other laboratory and industry applications. The most widely used method of protein structure determination is X-ray crystallography and obtaining high quality crystals is a crucial prerequisite for progress in this field. The difficulty of obtaining crystals of such complex molecules limits the success of these projects and brings the need for novel approaches in protein crystallization, based on understanding of the mechanisms and its constituent processes.

Besides structural biology, the formation of protein crystals and similar ordered arrays of folded proteins are of interest for several fields of science and technology. Nucleation, the first step of crystallization, constitutes an important step in the recognition and self-assembly processes which are part of the pathophysiology of protein aggregation-related diseases. Another area which relies on protein crystals is pharmacy: crystal dissolution at a controlled rate is used to achieve sustained release of medications, such as insulin, interferon-α, or the human growth hormone. In all of these areas control of crystallization hinges on the ability to achieve and control nucleation. Moreover, in the novel method of femtosecond X-ray protein nano-crystallography, which relies on crystals as small as 200 nm, the need to grow the crystals after they have nucleated is nearly eliminated and nucleation emerges as the sole process to be controlled.
Notwithstanding the importance of the nucleation process it is still one of the most secretive processes in chemistry, physics, materials science, biophysics and biotechnology. Due to its crucial place at the start of the crystallization process, the nucleation process determines the physical and chemical characteristics of the ordered solid phase. Hence, understanding the fundamentals of nucleation is crucial to get control over these properties.

It was demonstrated that nucleation of crystals of diverse materials (proteins, small organic and inorganic molecules, colloids, biominerals) in solution follows a two-step mechanism, according to which the crystalline nuclei appear inside metastable clusters of several hundreds of nanometers in size, which consist of dense liquid and are suspended in the solution. These dense liquid clusters were already detected during the Protein Crystallisation Diagnostics Facility (PCDF) mission. The cluster size varies from under one hundred to several hundred nanometers. The clusters occupy a low fraction of the solution volume: from ~10^{-7} (below which they are undetectable) to ~10^{-3}. The mesoscopic clusters have a lifetime in the order of seconds. They exist both in the homogeneous region of the phase diagram of the protein solution (where no condensed phases, liquid or solid, are stable or present as long-lived metastable domains) and under supersaturated conditions with respect to the ordered solid phase.

The most significant feature of the two-step mechanism of crystal nucleation is the correlation between the crystal nucleation induction time and the properties of the precursor clusters. This correlation provides a novel avenue for the control of the nucleation rate, by enhancing or suppressing the formation of the protein-rich clusters.
It is proposed to characterize the clusters and study the nucleation process in various mass transport regimes (diffusive, natural and forced convection).

The key fundamental questions to be addressed are (see also Table 2.7 in section 2.3):

- What is the effect of shear flow on the characteristics of the nucleation precursors?
- What is the effect of shear flow on nucleation, in particular on the nucleation induction time? How do the characteristics of the nucleation precursors evolve during the nucleation process?
- What is the effect of the presence of impurities on the nucleation induction times in the different mass transport regimes?
- Can crystal quality be improved by controlled nucleation via solution flow e.g. choice of mass transport regime?

The last fundamental key question can only be addressed after solving the previous questions.

Space relevance

The justification for the need of a space experiment stems from the fact that gravity may strongly influence the structural properties of growing structures. This is self-evident for protein crystallization.
The GRADFLEX experiment proved the existence of long range / long lived density fluctuations in space. Recent results by the ULB team provide evidence that these density fluctuations should have an impact on nucleation and on the dense liquid clusters. The Colloid experiment brought strong evidence that convection dramatically alters the kinetics of colloidal aggregation.

Solution convection may also enhance the nucleation of protein crystals in other ways:

- Shear flows are known to induce ordering in solutions and melts. It has been suggested that shear flow, by its inherent anisotropy, may enhance the ordering of the dense liquid in the precursor clusters, and in this way yield significant effects on the nucleation rate.
- Shear flows are known to induce partial protein unfolding. Thus, shear flows may enhance or suppress the formation of the nucleation precursors.

In a diffusive mass transport regime it is expected that, if an impurity is preferentially assimilated by the crystal, an impurity depletion zone will encircle the crystal leading to a relatively impure crystal nucleus encompassed by a pure outer shell. The opposite is true for impurities that are preferentially rejected by the crystal, leading to a crystal with a relatively pure nucleus in an impure outer shell.

2.3. Scientific Questions on Different Topics

Table 2.1: **Scientific Questions on Foam Physics**

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on space relevance
How do foams evolve with time, how does the bubble size increase, in particular when foams are wet? **Priority 1** **Significant progress expected in 2020**	Absence of drainage due to gravity, possibility to study wet foams over long times (24h)	How do wet foams (liquid fraction above 10%) coarsen? What is the role of the topological rearrangements? How is the nature of rearrangements changing close to the jamming limit? What is the influence of surface viscoelasticity, of bulk viscosity and of the presence of particles in the liquid (that could hinder the rearrangements and the liquid flow) ?	Foam stability (FOAM-S) Foam coarsening (SOFT MATTER DYNAMICS)	Wet foams are impossible to study on Earth for times longer than a few minutes, while coarsening is a slow process.

How does the transition solid-like to liquid-like mechanical response occur when stress is applied to a foam close to the jamming transition? Periodic yielding of such foams has been shown to induce a self-organized strengthening of the packing structure. Can this self-assembly process be used to make new soft materials with enhanced mechanical, optical or acoustic properties? **Priority 2** **First experiments planned before 2020 as follow-on series of experiments in SOFT MATTER DYNAMICS**	Absence of gravity drainage, possibility to study flow induced self-organization in wet foams (24h)	How does wet foam structure respond to a mechanical perturbation? How does a foam lose its rigidity close to the transition to a bubbly liquid? What is the role of topological arrangements (that are also present during coarsening), close to this jamming transition where the foam elastic modulus vanishes? How does cyclic flow induce structural self-organisation in disordered polydisperse foams ? How do these behaviours depend on bubble interactions which can be tuned via physico-chemical parameters ?	Foam stability (FOAM-S) Foam coarsening (SOFT MATTER DYNAMICS) Foam rheology subject of technology study to enable follow-on experiments in SOFT MATTER DYNAMICS);	Wet foams are impossible to study on Earth for times longer than a few minutes
How do aqueous foams behave in the presence of oil? Can oil be removed from the water using bubbles (as in flotation of minerals)? **Priority 2** **First experiments planned before 2020 (follow-on of SOFT MATTER DYNAMICS)**	Absence of gravity drainage, possibility to study wet foams including isolated bubbles over long times	How do wet aqueous foams containing oil coarsen? Are the oil drops adsorbed at the bubble surface? Do they spread on the surface?	Foam stability (FOAM-S) Foam coarsening (SOFT MATTER DYNAMICS)	Wet foams are impossible to study on Earth for times longer than a few minutes. Isolated bubbles rise under gravity even more quickly

Table 2.2 : Scientific Questions on Emulsion Physics

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved/ Relevant research topic	Related recent and future space experiment(s)	Comments on space relevance
How can we predict the structure, stability and rheology of emulsions and foams based on the knowledge of the interfacial properties of the related liquid/surfactant solutions? **Priority 1**	Weightless conditions. Purely diffusive conditions for surfactant transport.	Dynamic behaviour of liquid films and of adsorption layers/ Droplet coalescence. Emulsions and film stability.	FASES, FASTER, SOFT MATTER DYNAMICS. ZARM Drop Tower experiments on Oscillating Drops.	The suppression of buoyancy allows investigating the process of droplet aggregation/coalescence under simplified conditions, understanding the basic properties governing the phenomena and infer and test quantitative models to correlate them to the properties of the interfacial and liquid film properties. (see next row)
What is the dynamic behaviour of liquid films subject to mechanical stimuli? **How is it influenced by the presence of sub-micrometre/ nanometre particles?** **How does it reflect on the processes of droplet coalescence and aggregation?** **Are particles in a liquid film subject to some self-organisation?** **Priority 1**	Weightless conditions. Purely diffusive conditions for particle transport	Dynamic behaviour of liquid films and of adsorption layers/ Droplet coalescence. Emulsions and film stability.	FASES, FASTER, SOFT MATTER DYNAMICS. ZARM Drop Tower experiments on Oscillating Drops.	Studying the self-assembling properties of particles in films is important for applications in the field of developing new nanostructured/ microstructured materials, such as solid foams and nearly 2-D membranes. The possibility to investigate particle-stabilised films will be assessed. Possible interactions exists with the OASIS project since the concerned facility seems also suitable for these studies.

Are there capillary -driven regimes concerned with droplet dynamics in semi-dilute emulsions? **Priority 3**	Weightless conditions. Purely diffusive conditions for surfactant transport.	Chemically-driven droplet/ bubble dynamics/Emulsion stability. Breaking of dilute and semi-dilute emulsions (example, waste waters).	FASES, SOFT MATTER DYNAMICS	Weightless conditions, together with diffusive mass transport of surfactants allow the investigation and disclosure of specific bubble/ drop dynamics which are driven by the release of surfactant during drop/ bubble coalescence or coarsening. Such regimes, characterized by ballistic dynamics hypothesized for dilute and semi-dilute emulsions, cannot be studied on ground conditions due to the invasive presence of gravitational settling. Investigating these regimes can be useful to obtain a more complete picture of the processes involved in emulsion destabilisation and enable appropriate modelling. The SOFT MATTER DYNAMICS facility is particularly suitable for these studies.

What are the heat and mass transfer properties in emulsions (also particle-stabilised). **Priority 2**	Isolating dominant effect of heat and mass transport. Marangoni convection and nucleation phenomena.	Droplet freezing and coalescence. Nucleation. Marangoni stress. Propagation of solidification fronts in dispersed systems. Ostwald ripening (coarsening), micellar transport and composition coarsening. Synergetic effects between diffusion-driven and interfacial-controlled mechanisms.	FASES, ESA Technology programme on Infrared Spectroscopy (MATRA)	Mass transfer mechanisms in mixed emulsions with solute moving from one dispersed phase to the other across a bulk liquid is fundamental for the understanding of the ageing processes involved in emulsions. Due to the suppression of convection, weightless conditions are optimal to bring new insights into the understanding of the interplay between diffusion-driven phenomena and interfacial-controlled mechanisms in mixed emulsions. Understanding these processes is fundamental to develop further chemical processing (e.g., liquid-liquid fractioning, waste water treatments, etc. based on emulsion utilisation).

Table 2.3: Scientific Questions on Granular Matter Physics

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on space relevance
What is the onset of the gas/ clustering transition in a dissipative granular gas? How does such a granular gas deviate from the quasi-elastic limit (usual gas) when dissipation increases in the system? What is the phase diagram of dynamic states of a dissipative granular system? How does this out-of-equilibrium system return to equilibrium once the forcing is stopped (granular cooling). **Priority: 1 Significant progress expected by 2020**	Dynamics unaffected by the constant gravity force, and residual g-jitters, Particle interactions only driven by dissipative collisions, Isotropic motion of free particles, Absence of time scale due to gravity strongly simplifying the modelling.	Dissipative out-of-equilibrium systems Granular systems Granular gas Dissipative collisions Phase transitions Clustering formation Cooling Particle self-organization	The recent tests of VIP-Gran with the 2D and 3D cells on parabolic flights showed the compliance of the design and yielded preliminary results that match well recent numerical simulations. A cooperative experiment on the Chinese mission SJ-10 will investigate such behaviours though over a narrow range of experimental conditions. Next experiments with VIP-Gran on parabolic flights will serve to select the relevant range of experimental parameters. Covering the full range of relevant experimental parameters requires longer duration, and thus ISS. They can however be fully automated.	Parabolic flight experiments confirmed the occurrence of cluster formation. This cluster formation is still unexplored as is the deviation from its elastic limit. Parabolic flight experiments take place on too short timescales, and at low quality low-gravity. A higher quality of low gravity (to avoid g-jitters) and longer experimental runs are thus required to reach stationary regimes. Numerical simulations show that the typical time scale to reach stationary state is much larger than the timescale of the piston oscillation.

What are the internal structure and the large-scale dynamics of a granular medium driven by a convection-like mechanism (i.e. two walls vibrating with different velocities as a "thermal gradient"-like forcing)? **Priority: 1** **Significant progress expected by 2020**	Absence of convective flows due to gravity Absence of confinement pressure of grains due to their own weight Absence of sedimentation and residual g-jitters Particle interactions only driven by dissipative collisions Isotropic motion of free particles Absence of time scale due to gravity simplifying strongly the modelling.	Dissipative out-of-equilibrium systems Granular systems Convection process Thermal-like gradient Convection rolls	Recent: Parabolic flight experiments demonstrated the compliance of the VIP-Gran instrument with the ESR for the 2D and 3D cells. Preliminary results proved possible observation of convection rolls, however masked by j-jitters. Future: It is of high interest to study the effect of asymmetrical forcing in those systems in order to trigger convection-like dynamical patterns. This requires long experimental runs (ISS) that can be fully automated.	To mimic a "thermal gradient" forcing, two cell walls vibrate with different velocities and phases. The corresponding "cold" and "hot" walls are expected to drive the system into a convective-like motion. The relevant parameter that controls convection is not yet established without gravity. Parabolic Flight Campaign (PFC) experiments involve too short timescales, and a low level of low-gravity that mask the physical phenomenon. A higher level of low gravity (to avoid g-jitters) and longer experimental runs are thus needed (convective motions being expected to be slow). Numerical simulations show that the typical time scale to reach stationary state is much larger than the timescale of the piston oscillation.

How does a granular system composed of non-identical particles behave? **How to handle or to segregate a granular system composed of non-identical particles?** **Priority: 1** **Significant progress expected by 2020**	Dynamics unaffected by the constant gravity force, and residual g-jitters, Particle interactions only driven by dissipative collisions, Isotropic motion of free particles, Absence of time scale due to gravity simplifying strongly the modelling.	Dissipative out-of-equilibrium systems Granular systems Particle segregation Dissipative collisions Phase transitions Particle handling	Recent: on parabolic flights, clustering was demonstrated with the VIP-Gran instrument. Two granular species were also tested, showing that a few grains are able to trigger the clustering transition. Future: next parabolic flight experiments with VIP-Gran should confirm the segregation phenomena. ISS experiments are needed for longer runs in order to vary all parameters such as the concentration of both granular species. This can be done automatically.	PFC experiments involve too short timescales, and a low level of low-gravity that mask the physical phenomenon. A higher level of low gravity (to avoid j-jitters) and longer experimental runs are thus needed to reach stationary regimes. Numerical simulations show that the typical time scale to reach stationary state is much larger than the timescale of the piston oscillation.
What is the distribution of stresses inside a granular packing? **How do sound waves propagate in a granular packing and how fast?** **Priority 2**	Monitor stresses inside a granular packing both statically (compaction) and dynamically (sound) without the confinement pressure of grains due to their own weight, Using stress-birefringent particles immersed in an index matching liquid	Granular systems Sound waves Stress distribution Rheology Hertz contact	Recent: Parabolic flights in 2009 and 2015 Future: VIP-Gran cells for stress distribution, re-organisation by shearing, sound propagation or rheology studies.	Absence of the confinement pressure of grains due to their own weight.

What are the fundamental properties of light scattering from a homogeneous distribution of particles? **Priority: 1** **Significant progress expected by 2020**	Particles at rest or in a dynamic isotropic homogeneous state, variation of particle properties and correlations	Light scattering from dispersed particles shall be observed over long times to gain statistics and allow the particle system to come to rest	Experiments in the Drop Tower and Soft Matter Dynamics in ISS	System of particles without permanent contacts can only be prepared in the absence of sedimentation
How do dense granular systems evolve in the absence of gravity? **Priority: 1** **Significant progress expected by 2020**	Particles in homogeneous states both dynamic and quiescent or during cooling, i.e. energy loss; critical properties of granular packings	Light scattering reveals the granular dynamics, slow dynamics as precursor of both jamming and glass transition	Experiments in the Drop Tower and Parabolic flights Soft Matter Dynamics in ISS; Also: 3D stress-birefringent experiments in SpaceGrains	Homogeneous driving only possible in microgravity, especially for weak driving; absence of gravity allows closer approach to jamming transition as well as more homogeneous measurements
How does sound propagate in a granular packing close to the jamming transition? **Priority: 1** **Significant progress expected by 2020**	Detailed investigation of shock-wave transport (first priority) as well as scattering properties (second priority)	Close to the transition, particles losing contacts or forming additional ones, modify the sound transmission properties	Instrument SpaceGrains for ISS, related experiments in drop tower and parabolic flights	On ground, pressure gradient inside granular packing influences scattering
What is the rheology of shear-driven packings? **Priority: 2** **First experiments planned before 2020**	Time dependent rheology of a loose granular system with transient contacts among particles	Compression produces permanent contacts among particles at a defined jamming density; below that density, shear stress can produce transient contacts relevant for rheology	Instrument SpaceGrains for ISS	Under gravity, the loose system sediments and the shear-driven formation cannot be observed

Table 2.4: Scientific Questions on Complex (Dusty) Plasmas

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on space relevance
Microscopic properties of complex plasmas: charging of particles, particle-particle interactions, particle-plasma interaction	Determination of particle charges for various pressures, particle sizes and dc currents Measurement of the ion drag force acting on particles	Measurement of particle velocity	PK-4	Accurate velocity measurement in the bulk plasma at the tube centre (only in space) for various pressures, DC-currents, and particle sizes.
Macroscopic properties of complex plasmas: thermodynamics (e.g. equation of state), phase transitions, transport coefficients, collective behaviour (e.g. waves, instabilities, turbulence)	Investigation of dust waves and instabilities Creation of shear flow by laser manipulation and determination of viscosity Investigation of Laval nozzle, shock waves, Mach cones, and rarefaction waves using laser manipulation and the internal electrode (EM)	Image analysis of the micro-particle system, measurement of particle positions and velocities	PK-4	Undisturbed microparticle system (no sedimentation)
Generic properties of classical many-body systems: complex plasmas as model system for the dynamic behaviour of atomistic systems in solid state, fluid, statistical and plasma physics on the microscopic level and in real time	Investigation of phase transitions, e.g., order, critical exponents, universality classes, and critical points Self-organisation Crystallization (crystal growth, defects, boundaries) Lane-formation studying interpenetrating particle clouds Transition from laminar to turbulent flow Electro-rheology (string formation of particles in an external electric field)	Image analysis of the micro-particle system, measurement of particle positions and velocities	PK-4	Undisturbed microparticle system (no sedimentation)

Table 2.5: Scientific Questions on Interactions in Cosmic and Atmosheric Particle Systems

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on space relevance
Evolution and growth of dust aggregates in protoplanetary disks		Absence of sedimentation; control over thermophoretic motion and thermal creep		Ultralow velocities; very long agglomeration timescales; absence of size separation and de-mixing; absence of compaction due to handling
I. Brownian motion driven growth	Measure mass-frequency distribution function; measure fractal dimension; measure temporal evolution of aggregate masses; determine role of rotational Brownian motion	Brownian motion kinematics; hit-and-stick aggregation	CODAG (STS-95); CODAG-SRE (Maser 10); future: cloud manipulation system (CMS), high-speed long-distance microscopy (LDM)	
II. Onset of compaction	Control collision velocities among dust aggregates	Dynamics of fluffy aggregate collisions; aggregation with compaction	Future: CMS; LDM	
III. Evolution of fractal dimension during growth with compaction	Control collision velocities among dust aggregates	Ensemble behaviour of aggregates at non-hit-and-stick collisions	Future: CMS; LDM	

IV. Does bouncing occur?	Determine the highest velocity for which sticking occurs; determine whether bouncing or fragmentation follow at even higher velocities; critical point: aggregates must be grown during ballistic growth stage to represent realistic morphologies	Energy partition in aggregate collisions	Future: high-speed imaging	
V. Role of cosmic radiation	Radiation-aggregate interactions	Collisions of swift particles and photons with monomers and aggregates in low gravity experiments	Dynamics of aggregations: electromagnetic forces, van der Waals forces, short-distance surface contact	
Can light scattering reveal the nature of dust aggregates?	Measure light scattering properties of well-characterized dust aggregates	Interaction of dispersed matter with electromagnetic radiation, including polarisation	CODAG-SRE (Maser 8); PROGRA2 on parabolic flights; Light Scattering Unit (LSU)	

Fundamental aspects of transport phenomena in dust clouds				
I. Choice of adequate models for rarefied gas dynamic description of particle and gas motion	Reference data on thermo-, photo-, diffusiophoresis, various phoreses from accommodation non-homogeneities; drag force; thermal creep and thermal stress induced flows; microphysics of particle interaction	Motion of free floating dust particles (isometric and non-isometric compact grains, agglomerates of various fractal dimensions). Sources of motion: thermal and concentration gradients in gas; illumination; physico-chemical reaction on particle-gas interface (catalytic, photo-evaporation, etc.). Research goals: accurate reliable data on transport coefficients	JET (MASER 8); PFC and Drop Tower (DT) campaigns. Future: DT campaigns (CMS, dedicated cells for force measurements, long distance microscopy, eventually digital holographic microscopy, additional sources of particle in situ injection, manipulators). DT campaigns primarily dedicated to transport properties; such measurements are planned to be done in parallel to agglomeration research on Sounding Rockets or other long duration space platforms.	Current experimental data are of low accuracy and in a very limited range of Knudsen number (Kn=0.1-10), ratio of conductivities, accommodation coefficients, type of gases. Microgravity allows accurate measurements in a wide range of parameters that is crucial to check the models
II. Transition to, and manifestation of, non-linear response in heavy mass-loaded dust-gas clouds	Put forward coupling in interaction on different levels: particle-particle via gas, dust-gas and dust-gas-light with emphasis on rapid forced agglomeration	Among the variety of mechanisms: force between particles due to their thermal interaction; thermophoretic particle motion that modifies temperature gradient, also when particles are a source of heat/mass release; internal convection in a cloud of limited size moving in external force field; particle streaming; etc.	Same as in the cell above	Suppression of cloud sedimentation and gravitational convection. Ultralow velocities; long observation times required due to high dust-gas coupling time

III. Transition peculiarities of dust-gas clouds to and from granular matter systems	Particle motion and agglomeration in the zone of transition from thermal to pure ballistic regime	Mechanisms: modification of particle velocity distribution function; growth role of inter-particle forces. Topics: agglomeration kinetics and agglomerate dimensionalities; cooling kinetics	Future: Modified CMS on Drop Towers; cooling on Sounding Rockets or any other long duration space platform	A cloud of solid particles should levitate practically in vacuum that is possible only in space.

Table 2.6: Scientific Questions on the Physics of Colloids

Open fundamental scientific questions	Soft Matter systems to be investigated	Related recent and future space experiment(s)	Comments on space relevance
For dense suspensions of repulsive colloids in space, are anomalously fast relaxations observed? What is their dependence on the particle volume fraction and on the probed spatial scales?	Highly concentrated suspensions of PMMA/pNIPAM colloidal particles	Planned for experiments with the COLLOIDAL SOLIDS facility	Avoiding gravitational stresses, which can propagate through a colloidal solid structure
Can dynamical heterogeneities, namely, temporal fluctuations and spatial correlations of the dynamics, be detected?			
Does the depletion gel scenario highlighted by ground experiments drastically change in the absence of gravity?	Suspension of MFA optically anisotropic particles + non-ionic surfactants acting as depletant.	To be studied on NASA ACE-T mission (expected first flight in spring 2016). Planned for experiments with the COLLOIDAL SOLIDS facility.	Avoiding gravity collapse of weak gel, and contribution to restructuring of strong gels due to gravitational stress
Can the existence of internal stress-relaxation mechanisms, suggested by the experimental evidence obtained on ground, be confirmed and better highlighted in space?			

How does self-assembly of patchy particles depend on valency and interactions strength?	Patchy colloidal particles dispersed in picoline + water mixtures	Previous measurement on isotropic particles (SODI Colloid) To be studied on NASA ACE-T mission and planned for experiments with the COLLOIDAL SOLID facility	Avoiding sedimentation effects on aggregates
How much flexibility and control of the self-assembled structures is actually gained by working in space, with respect to ground experiments?			
What are the annealing effects on a colloidal glass or gel due to a cyclical thermal stress?	All aforementioned colloidal systems	Planned for experiments with the COLLOIDAL SOLIDS facility	Avoiding convection due to horizontal temperature gradients
What are the structural perturbations induced at steady-state by local heating on a colloidal structure where inter-particle interactions are temperature dependent?			

Table 2.7: Scientific Questions on the Physics of Macromolecules

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on space relevance
What is the effect of shear flow on the characteristics of the nucleation precursors?	Diffusive mass transport regime	Characterization of the dense liquid clusters in under-saturated conditions: What is the influence of a diffusive mass transport regime on the size and volume fraction of the clusters?	Previous: observation of dense liquid clusters during PCDF experiments. Future: COLLOIDAL SOLIDS (ESA) Light Microscopy Module (LMM, NASA): DDM (Differential Dynamic Microscopy)	The GRADFLEX experiment proved the existence of long-range/long-lived density fluctuations in space. Recent results by the ULB team provide evidence that these density fluctuations should have an impact on the characteristics of the dense liquid clusters
What is the effect of shear flow on nucleation in particular the nucleation induction time? How do the characteristics of the nucleation precursors evolve during the nucleation process?	Diffusive mass transport regime	Measurements of nucleation induction times statistics. Evolution of the characteristics of the dense liquid clusters during a nucleation process.	Future: COLLOIDAL SOLIDS (ESA): Turbidity measurements Dynamic Light Scattering (DLS) in combination with cDDLS (confocal Depolarized DLS)	The SODI-Colloid experiment brought strong evidence that convection dramatically alters the kinetics of colloidal aggregation. Shear flows are known to induce ordering in solutions and melts. It has been suggested that shear flow, by its inherent anisotropy, may enhance the ordering of the dense liquid in the precursor clusters, and in this way yield significant effects on the nucleation rate.

What is the effect of the presence of impurities on the nucleation induction times in the different mass transport regimes?	Diffusive mass transport regime	Measurements of nucleation induction time statistics in the presence of impurities. Characteristics of nuclei (e.g. size, number) in the presence of impurities.	Future: COLLOIDAL SOLIDS (ESA): Turbidity measurements DLS in combination with cDDLS (confocal depolarized DLS)	The Colloid experiment brought strong evidence that convection dramatically alters the kinetics of colloidal aggregation. In a diffusive mass transport regime it is expected that if an impurity is preferentially assimilated by the crystal, an impurity depletion zone will encircle the crystal leading to a relatively ‘impure’ crystal nucleus encompassed by a pure outer shell. The opposite is true for impurities that are preferentially rejected by the crystal, leading to a crystal with a relatively pure nucleus in an impure outer shell.

2.4. Benefits to Industry

2.4.1. Industry Partners to the Roadmap

ABN (ES)
GRANUSYS (BE)
Nestle (CH)
IFPEN (FR)
Teclis (FR)
Loufakis Chemicals (GR)
Pohltec Metalfoam GmbH (DE)

Industry in general benefits from the better understanding of the processes involved when dealing with soft-matter systems. For example, in light scattering, the scattering from a non-sedimenting particle arrangement is a vital limiting case to assess the validity and interpretation of earth-bound measurements. Similarly, the experiments in weightlessness offer the possibility to confront existing models with simple situations that are not available for testing on ground. Hence, soft matter in microgravity promises progress both for the refinement of experimental methods as well as in modelling.

Nestlé has demonstrated a strong interest in low gravity experimentation with several research scientists involved in this research area with ESA in the last few years. Nestlé is still interested in the investigation of the stabilization and destabilization process of food formulations and some key-information can only be obtained in low-gravity conditions, both in parabolic flights and on ISS. As an example a deep understanding of the mechanism of action of the polyglycerol ester, a lamellar phase forming surfactant, in an aerated product would help to optimize recipe and process. Microgravity experiments will help to clarify the impact of the liquid drainage around the air bubbles in the coarsening mechanism. In addition, emulsions as well as granular matter also are fields of active research at Nestle, where future collaboration can be expected with the Soft Matter Dynamics science team.

Industry benefited significantly from the research work on metallic foams already performed on parabolic flights and a sounding rocket flight. It made it possible to demonstrate the crucial role of the blowing agent employed on the coarsening process of metallic foams, supported by comparison with aqueous foams. This led to the development of a new alloy composition with improved pore structure. Additional work will permit further advancements in the product quality and process stability of this material for more advanced industrial applications.

Petroleum recovery makes use of large quantities of water which becomes contaminated during oil production. IFP Energies Nouvelles is currently investigating a new process for the removal of crude oil from water using air bubbles (flotation). Space experiments with well-designed model systems will allow the characterization of the behaviour of oil at the surface of bubbles. This is of great interest for developing knowledge and getting a better understanding of the behaviour of these complex systems.

Teclis is a small company specialized in instrumentation dedicated to liquid interfaces and foams. Teclis is interested in the characterization of physicochemical properties, including surface viscoelasticity, thin film behaviour and 2D foams. Teclis is also interested in the potential use of Diffusing-wave spectroscopy (DWS) in foam characterization. Teclis participates and contributes to the Soft Matter Dynamics project where these methods will be used.

Loufakis Chemicals is specifically interested in a better understanding of the effects and phenomena occurring when adding engineered particles to polymeric emulsions (nanolatexes) used for protective coatings and in which droplet coalescence is one of the important processes involved in the formation of the coating film. This will allow them to improve the performance of their commercial polymeric emulsions, adapting concepts and also procedures that may emerge as a result of the space projects. In fact, due to the need for more environmental friendly products and the guideline of the European Union, to stop the use of volatile organic compounds (VOC) in paint formulations (Directive 2004/42/EC), the company is investigating latex-based emulsion coatings that emit less organic solvents into the atmosphere.

A fundamental understanding of light scattering from mesoscopic particles (e.g., granular matter) in dense but not sedimented systems is a prerequisite for its implementation in applications such as devices for particle (size) characterization, process monitoring, and quality control. Across Europe, such instruments are typically produced and brought to market by small- and medium-sized enterprises that are highly innovative in their respective niches. A survey lists seven manufacturers of light-scattering instruments in Europe alone among more than twenty worldwide. These SMEs benefit from the outcomes of the research in microgravity. Sound measurements are of similar importance to the processing industry, and results from microgravity promise similar impact.

The relevance of nucleation in macromolecule solutions to industry relates to the following:

- First of all there is interest in the context of drug design: structures at high resolution are a prerequisite for this process and nowadays this can be obtained from micron-size crystals (nuclei).
- Secondly nucleation as a first step in the crystallization process determines the main properties of the crystal population: crystal polymorph, number of crystals, their size and size distribution and others. This is important for the production of, amongst others, active pharmaceutical ingredients (APIs).

ROADMAP 3: TWO-PHASE HEAT TRANSFER RESEARCH PLAN IN SPACE

3.1. Introduction

It is the common understanding of the Two-Phase Heat Transfer International Topical Team (ITT) that research in the relevant fields of engineering is carried out with the aim to improve existing devices and processes, and to come up with new applications. As all technical applications are based on physical phenomena, a comprehensive understanding of these phenomena is mandatory to derive design tools and methods for optimization of the application.

In order to reach a better understanding of the underlying processes, studying the phenomena experimentally and numerically/analytically is necessary. These approaches should be coupled, as numerical codes or analytical models require validation, which can be provided by experiments. Experimental results on the other hand can be better explained through analytical models and/or numerical calculations as they typically provide higher temporal and/or spatial resolution and provide access to additional quantities with respect to the experimental databases.

This philosophy is depicted in Figure 3.1. The schematic is specific to reduced gravity research. Nevertheless, by omitting the "study phenomena in generic experiments in microgravity" step, the principle is fundamentally a valid representation of the strategy of the Science Team members for ground based studies.

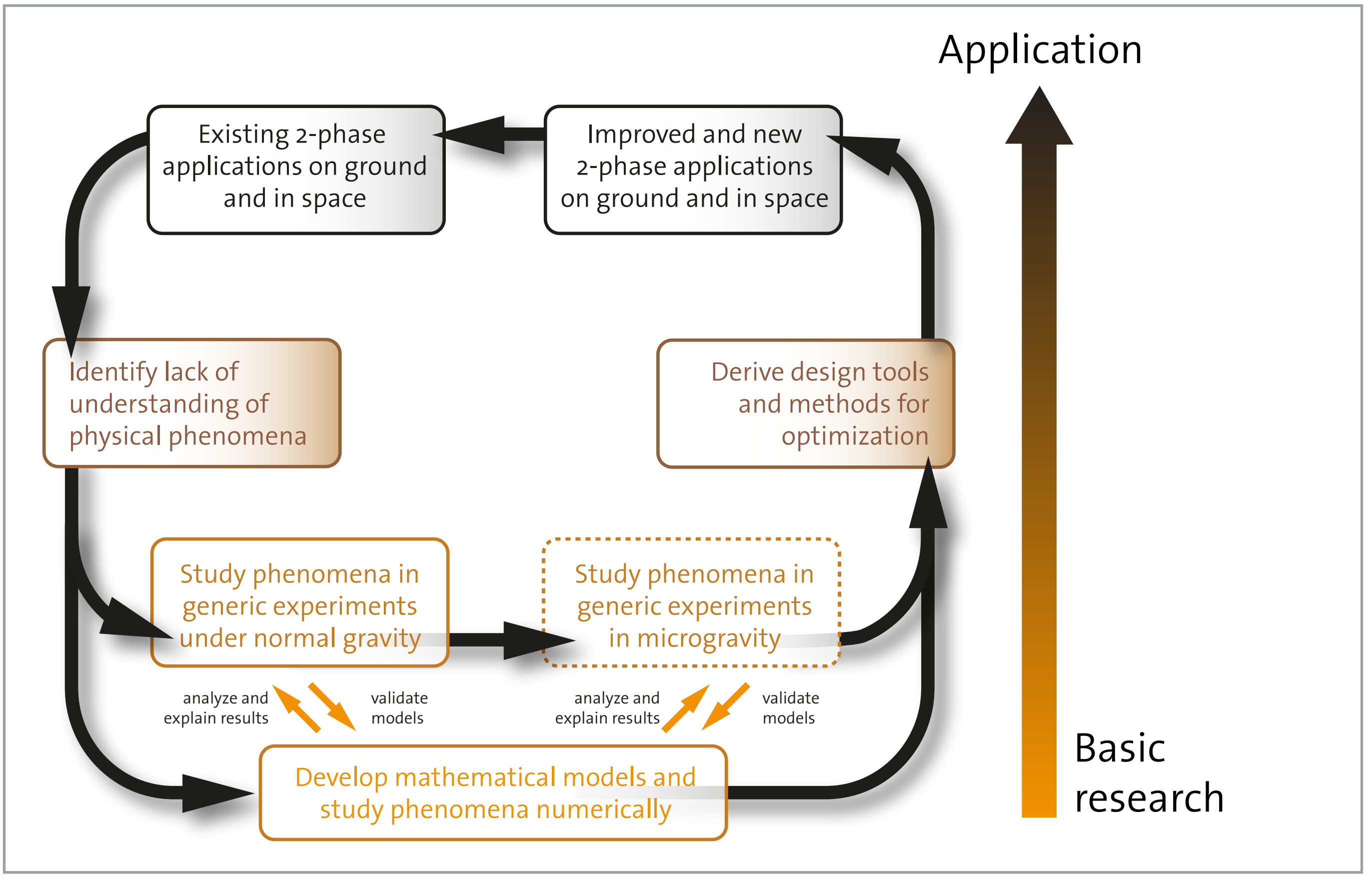

Figure 3.1: Common research approach for ground and microgravity two-phase heat transfer research

3.2. Categorization of Research Topics

The Two-phase Heat Transfer International Topical Team deals specifically with gas-liquid phase change related phenomena with the continuous motivation of improving heat transfer devices in space as well as in terrestrial applications. At the time of writing the present document the majority of heat transfer devices rely on single-phase processes, involving heat conduction and diffusive processes, with or without convection. However, systems exploiting phase change, and thus latent heat, promise to transfer larger amounts of heat at small temperature differences, which is a highly desirable achievement in practical applications. Such systems are typically more compact, also reducing the environmental impact on the utilisation of resources. They have already emerged in numerous applications, e.g. heat pipes in space and on ground, power plants, air conditioners, industrial boilers, and 2-phase cooling loops. But due to the gaps in the understanding of the underlying processes, their performance is typically tuned empirically, which requires either a substantial effort to achieve an optimised solution or an oversized design.

Consequently, the goal of the present International Topical Team is to advance the understanding of the underlying physics of gas-liquid phase change processes and ultimately describe the findings in theoretical and numerical models that can be used for optimising practical applications at their design phase (as described in section 3.1).

Heat transfer has been in the centre of scientific studies for centuries on ground and for a few decades in microgravity conditions. Previous space experiments demonstrated the large-scale behaviour of two-phase systems in weightlessness. The community turns now towards multiscale investigations aiming at a quasi-complete description of physical phenomena relevant down to nanometre scales. The goal for the foreseeable future is to assess processes, which are difficult to be addressed in the presence of the gravitational acceleration field.

This section lists the main research areas in two-phase heat transfer (valid at the time of issuing the present document) with the aim of identifying all the underlying physical phenomena that require the attention of scientific studies.

The research topics of two-phase heat transfer can be structured by arranging them around three main areas, representing very basic physical processes: evaporation, condensation and wetting. This is illustrated in Figure 3.2.

The physical phenomena that have an influence in the different processes can be grouped in three categories: phenomena that are limited to the fluid(s), phenomena that are specific to the wall and phenomena that play a role in fluid/wall interactions. This structure of physical phenomena is illustrated in Figure 3.3.

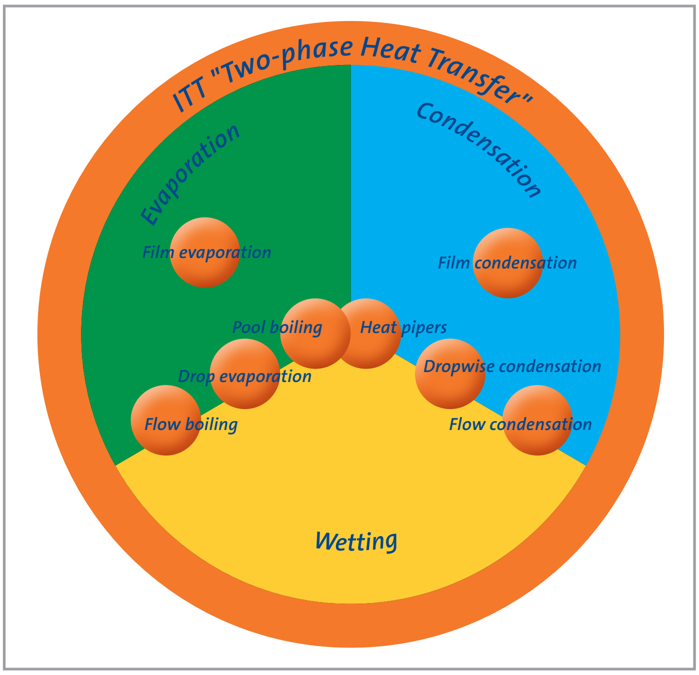

Figure 3.2: Categorization of research topics within two-phase transfer research

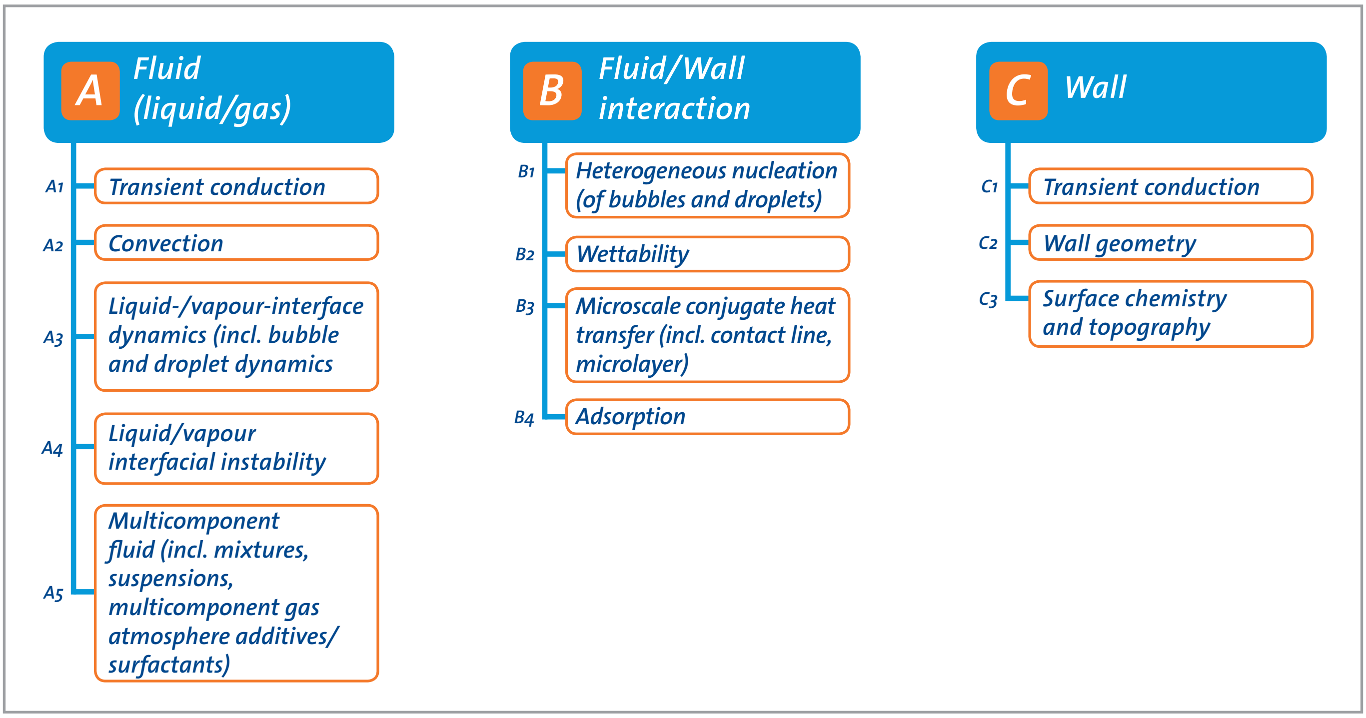

Figure 3.3: Underlying physical phenomena that influence evaporation, condensation and/or wetting

3.3. Physical Phenomena to be Investigated in Two-phase Heat Transfer

Based on the physical phenomena shown in Figure 3.3, a summary of the currently open fundamental scientific questions for each phenomenon is listed in Figure 3.4 to provide a global overview.

A Fluid (liquid/gas)

A1 Transient conduction
A1-1: What is the contribution of transient conduction in periodic phase change processes?

A2 Convection
A2-1: What are the dominant mutual interactions between the liquid-vapour interface displacement and the dynamic changes of the thermal boundary layer, and how do they influence the local heat transfer mechanisms?
A2-2: What is the relative contribution of different convection mechanisms (forced, natural, Marangoni) in mixed convection regimes?
A2-3: What is the contribution of thermocapillary/Marangoni convection to the overall energy transport at a liquid-vapour interface?

A3 Liquid-vapour-interface dynamics (incl. bubble and droplet dynamics)
A3-1: What are the dominant mechanisms of interfacial coalescence and breakup, and how can we describe them?
A3-2: What are the effects of coalescence or breakup on local heat and mass transfer?
A3-3: What is the influence of an external force field (e.g. gravity, electric field, shear flow) on the liquid-vapour interface dynamics?
A3-4: How to predict flow regimes for a wide spectrum of parameters (fluid, wall and process parameters)?
A3-5: How to predict heat transfer coefficient and pressure loss (if applicable) for the different flow regimes?

A4 Liquid-vapour interfacial instability
A4-1: What triggers liquid-vapour interface instabilities?
A4-2: How do interface instabilities lead to breakup?
A4-3: How does interface instability influence heat transfer characteristics?

A5 Multicomponent mixture (incl. mixtures, suspensions, multi-component gas atmosphere, additives/surfactants)
A5-1: How to predict the local concentration of volatile components in a mixture at a liquid-vapour interface?
A5-2: What is the impact of a discrete phase (e.g. particles) in the bulk fluid and at the interfaces?
A5-3: What is the effect of non-condensable gases?
A5-4: What is the impact of additives/surfactants at quasi-static and dynamic interfaces?
A5-5: How to predict heat transfer properties in emulsions?

B Fluid/Wall interaction

B1 Heterogeneous nucleation (of bubbles and droplets)
B1-1: What are the dominant mechanisms and parameters of heterogeneous nucleation?
B1-2: How can nucleation site activation and active site density be predicted?

B2 Wettability
B2-1: How can the influence of different parameters on wettability be predicted?
B2-2: How does the wettability influence contact line dynamics?

B3 Microscale conjugate heat transfer (incl. contact line, microlayer)
B3-1: What is the role of heat transfer mechanisms (contact line, microlayer, transient conduction) under various circumstances (fluid, wall and process parameters)?
B3-2: How does local heat transfer influence wetting characteristics and vice versa?

B4 Adsorption
B4-1: How does particle adsorption influence nucleation?
B4-2: How does adsorption influence wetting characteristics?
B4-3: How to predict adsorption and energy transport across an adsorbed film?
B4-4: What is the influence of heat transfer on desorption properties and chemical alteration of porous materials?

C Wall

C1 Transient conduction in the wall
C1-1: What is the influence of the thermal characteristics of the wall material on the conjugate solid-fluid heat transfer?

C2 Wall geometry
C2-1: What is the effect of substrate geometry and size (mini- and microscale) on the liquid-vapour interface?

C3 Surface chemistry and topography
C3-1: What is the effect of thermal surface topography/chemistry on the liquid-vapour interface dynamics?
C3-2: Can the surface topography/chemistry be used/designed to enhance heat transfer?

Figure 3.4: Fundamental questions at a glance

Further details on each question are given in Table 3.1 , including those space experiments, which are already planned or recently carried out to address at least partly the relevant scientific questions. Here, priorities are also included, together with a target date by which the question is considered to be tackled (not necessarily resolved entirely). As the required studies need to rely on extensive fundamental basic research and a wide spectrum of parameters, it is clear that single experiments do not necessarily provide conclusive answers to the scientific questions.

In the "Mechanisms involved / Relevant for research topic" column of Table 3.1 the relevant research topics are listed. Those, which are partially connected to the given question, are indicated with generic characters. Those, which are fundamentally concerned, are indicated with bold and underlined characters.

3.3.1 About Microgravity Relevance

In Table 3.1 the following considerations were taken into account at the definition of the focus of the space experiment(s) and at the comments on the microgravity relevance.

The mechanisms of two-phase heat and mass transport depend on strongly coupled thermal and mechanical influences acting between the gas (vapour), liquid and solid phases. Although major progress has been made over the past century with regard to understanding the fundamental science of two-phase flow and heat transfer, the preponderance of knowledge has been produced through experimental research and the overwhelming majority of the experiments have been performed in terrestrial gravity. Earth's gravity inhibits the progress of fundamental understanding of two-phase flow and heat transfer for the following prominent reasons:

- Gravity produces buoyancy-driven flow. In thermal fields, highly stochastic buoyant natural convection flow fields occur in the fluid phases. The thermally-driven buoyancy flows are typically coupled with, and often overshadow, other important underlying physical phenomenon (thermocapillary flows, bubble-induced convection, transient thermal diffusion etc.). The highly non-linear coupling makes it extremely difficult to disentangle the separate influences making scientific understanding problematic.
- Gravity mechanically interacts with immersed bodies. Gas and liquid phases have density differences spanning several orders of magnitude. When one phase is immersed in another and exposed to a gravitational field, hydrostatic stresses cause vertically-orientated forces that act on immersed masses, often inducing gravity-induced motion of the mass, including lift on bubbles and stratification of liquids. Also, if the hydrostatic pressure gradients are comparable or exceed surface tension stresses (e.g. bubbles and drops), they may also cause shape distortions which, when interacting with other mechanical stresses at the interface (e.g. hydrodynamic), result in two phase structures of complex shapes with equally complex models required to resolve them. Zero gravity thus lends itself to clear evaluation and understanding of natural stresses (e.g. static pressure, capillarity) and/or imposed stresses (e.g. shear, electrostatic) on two phase flows.
- Gravity encourages rapid and small phenomenological events. When gravity dominates, two-phase flow structures and events (bubble departure, interface instabilities etc.) tend to occur at time and length scales that strain the capabilities of scientific measurement equipment. Eliminating gravity exposes physical phenomenon in such a way that facilitates high temporal and spatial resolution offering substantially deeper physical insight into underlying physical phenomena.

Ultimately, long duration zero-gravity experiments will provide unencumbered insight into two-phase flow and heat transfer phenomenon. This will establish correct understanding which will lead to exact theories and accurate models which can subsequently be used to deepen scientific knowledge and/or create new technologies or improve existing ones. It is within these contexts that the following core open scientific questions are posed.

Table 3.1 Detailed list of research topics

Priorities are defined as follows: 1 = highest priority, 5 = lowest priority)

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A1-1) What is the contribution of transient conduction in periodic phase change processes? **Priority: 3** **Significant progress expected by 2020**	Absence of buoyant convection	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	Recent: BXF/MABE, BXF/NPBX, Flow Boiling and Condensation Experiment (FBCE), Boiling Two-Phase Flow Experiment (TPF) Future: Multiscale Boiling (RUBI), Thermal Platform inserts (Boiling, Flow Boiling, In-Tube Condensation, Pulsating Heat Pipes) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Pulsating Heat Pipe, Two-phase Flow Loop in Space, Spray Cooling in Space	During the assessment of the destruction and regrowth of the thermal boundary layer (i.e. transient conduction), caused by two-phase flow dynamics, on heat and mass transfer processes, as the temperature distribution is difficult to characterize experimentally, and with temporally varying phase distribution it is difficult to model, isolating the system from the effect of the stochastic buoyant natural convection significantly reduces the complexity of the system under study. Thus, the associated assessments may be aided by benchmark cases performed in weightlessness.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A2-1) What are the dominant mutual interactions between the liquid-vapour interface displacement and the dynamic changes of the thermal boundary layer, and how do they influence the local heat transfer mechanisms? **Priority: 1** **Significant progress expected by 2024**	Absence of stratification and buoyant convection	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	BXF/MABE, BXF/NPBX, Flow Boiling and Condensation Experiment (FBCE), Boiling Two-Phase Flow Experiment (TPF), Multiscale Boiling (RUBI), Thermal Platform inserts (Boiling, Flow Boiling, In-Tube Condensation, Drop Evaporation, Self-rewetting Fluid, Pulsating Heat Pipes, Condensation on Fins, Enhanced Evaporators, Marangoni in Films, Shear Driven Film) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Pulsating Heat Pipe, Two-phase Flow Loop in Space, Spray Cooling in Space	As the complex temperature distribution of a gas (vapour)-liquid two-phase system is difficult to characterize experimentally, and with temporally varying phase distribution it is difficult to model, isolating reference configurations from the effect of buoyancy significantly improves the reliability of measurements. Thus, the associated assessments may be aided by benchmark cases performed in weightlessness.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A2-2) What is the relative contribution of different convection mechanisms (forced, natural, Marangoni) in mixed convection regimes? **Priority: 1** **Significant progress expected by 2020**	Absence of buoyant convection	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Evaporation Patterns (CIMEX), Multiscale Boiling (RUBI), Flow Boiling and Condensation Experiment (FBCE), Boiling Two-Phase Flow Experiment (TPF), Thermal Platform inserts (Boiling, Flow Boiling, In-Tube Condensation, Drop Evaporation, Self-rewetting Fluid, Pulsating Heat Pipes, Condensation on Fins, Marangoni in Films, Shear Driven Film) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Pulsating Heat Pipe, Two-phase Flow Loop in Space, Spray Cooling in Space	Determining the precise mechanism and contribution of e.g. shear stress or Marangoni convection at the gas-liquid interface is key in evaluating the relative importance in terrestrial configurations. Multicomponent liquids also lead to (interfacial) concentration distribution, representing an additional level of complexity in mixed convection. Thus, avoiding the additional effects of gravity by accurate investigation in weightlessness allows more precise investigation of these phenomena alone. In some cases this also allows to scale up the configurations studied, for more accurate visualization and validation of numerical codes.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A2-3) What is the contribution of thermocapillary/Marangoni convection to the overall energy transport at a liquid-vapour interface? **Priority: 3** **Significant progress expected by 2020**	Absence of buoyant convection, scaling up length scales	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Evaporation Patterns (CIMEX), Thermal Platform inserts (Boiling, Drop Evaporation, Self-rewetting Fluid, Marangoni in Films, Shear Driven Film) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Pulsating Heat Pipe, Two-phase Flow Loop in Space, Spray Cooling in Space	Natural convection superimposes on and often supersedes thermocapillary convection and thus masks its contribution to energy transport. Therefore, benchmark cases are recommended to be evaluated in weightlessness. Scaling up is also recommended here, for a more accurate visualization and validation of numerical codes.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A3-1) What are the dominant mechanisms of interfacial coalescence and breakup, and how can we describe them? **Priority: 3** **Significant progress expected by 2024**	Increasing length scales, avoiding buoyancy-driven effects (bubble coalescence)	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	BXF/MABE, BXF/NPBX, Flow Boiling and Condensation Experiment (FBCE), Boiling Two-Phase Flow Experiment (TPF), Multiscale Boiling (RUBI), Thermal Platform inserts (Boiling, Flow Boiling, In-Tube Condensation, Self-rewetting Fluid, Pulsating Heat Pipes, Enhanced Evaporators, Marangoni in Films, Shear Driven Film) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Pulsating Heat Pipe, Two-phase Flow Loop in Space, Spray Cooling in Space; boiling crisis research within DECLIC programme	While interfacial coalescence and breakup can be studied on ground to a large extent, a detailed study at a microscopic level of the interface dynamics for multiple species fluid can be better made in microgravity in order to eliminate the effect of density which, especially for fluid with solid particles, can be rather important. In this sense microgravity experiments are suitable for getting a picture of the separate influence of Marangoni forces, adhesion forces, particle migration due to concentration and temperature gradients.

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Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A3-2) What are the effects of coalescence or breakup on local heat and mass transfer? **Priority: 2** **Significant progress expected by 2020**	Increasing length scales, avoiding buoyancy-driven effects (bubble coalescence)	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Recent: BXF/MABE, Future: Multiscale Boiling (RUBI), Thermal Platform inserts (Boiling, Flow Boiling, In-Tube Condensation, Self-rewetting Fluid, Pulsating Heat Pipes, Enhanced Evaporators, Marangoni in Films, Shear Driven Film) SOBER-SJ10 (Single bubble pool Boiling Experiment aboard SJ-10) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Pulsating Heat Pipe, Spray Cooling in Space; boiling crisis research within DECLIC programme	The effects of coalescence or breakup on local heat transfer can mostly be addressed on ground. However, in particular thin liquid film, sessile drop or bubble-based systems, where buoyancy-driven phenomena may also play a role, are recommended to be addressed in weightlessness.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A3-3) What is the influence of an external force field (e.g. gravity, electric field, shear flow) on the liquid-vapour interface dynamics? **Priority: 1** **Significant progress expected by 2020**	Increasing length scales, avoiding buoyancy-driven effects, buoyancy-driven interface deformation	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Flow Boiling and Condensation Experiment (FBCE), Electrically Driven Liquid Film Flow Boiling in the Absence of Gravity Boiling Two-Phase Flow Experiment (TPF), Multiscale Boiling (RUBI), Evaporation Patterns (CIMEX), Thermal Platform inserts (Boiling, Flow Boiling, In-Tube Condensation, Drop Evaporation, Pulsating Heat Pipes, Shear Driven Film) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Two-phase Flow Loop in Space, Spray Cooling in Space	Most interfacial phenomena in terrestrial conditions are ruled by gravitational forces that mask the effect of other parameters. Their influence, however, can be important at the microscale. Studies in microgravity enlarge the characteristic lengths of the system allowing a better investigation. Furthermore, from an application point of view, these studies reveal to what extent other forces may replace buoyancy in microgravity restoring heat transfer performance closer to a terrestrial one.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A3-4) How to predict flow regimes for a wide spectrum of parameters (fluid, wall and process parameters)? **Priority: 2** **Significant progress expected by 2024**	Dominant effect of inertia and capillary forces	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Flow Boiling and Condensation Experiment (FBCE), Boiling Two-Phase Flow Experiment (TPF), Evaporation Patterns (CIMEX), Thermal Platform inserts (Flow Boiling, In-Tube Condensation, Pulsating Heat Pipes, Shear Driven Film) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Pulsating Heat Pipe, Two-phase Flow Loop in Space	Precise determination of flow regimes in weightlessness (and at various gravity levels) is important for the design of space-based systems and technologies used in space exploration missions. Wall shear stress and wall heat transfer are strongly dependent on flow regimes. Modelling of the physical mechanisms responsible for the transition between flow regimes is the unique hope to get predictive models in a wide range of parameters. The ranges of parameters for which microgravity is relevant has to be clearly defined thanks to dimensionless numbers

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A3-5) How to predict heat transfer coefficient and pressure loss (if applicable) for the different flow regimes? **Priority: 1** **Significant progress expected by 2024**	Dominant effect of inertia and capillary forces	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Flow Boiling and Condensation Experiment (FBCE), Boiling Two-Phase Flow Experiment (TPF), Evaporation Patterns (CIMEX), Thermal Platform inserts (Flow Boiling, In-Tube Condensation, Pulsating Heat Pipes, Shear Driven Film) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Pulsating Heat Pipe, Two-phase Flow Loop in Space, Spray Cooling in Space	The effect of gravity superimposes on other processes (e.g. those driven by surface tension and inertia) in certain regimes. Thus, benchmark cases are needed to elaborate on the delicate underlying interplay. In flow boiling, nucleate boiling regimes and convective boiling regimes have to be identified. In annular flow configuration, heat transfer is closely related to the structure of the liquid film (velocity, thickness, interfacial waves) → need of local analysis of the liquid film structure through specific measurements, theoretical approaches or numerical simulations. The development of interfacial waves strongly depends on buoyancy, inertia, viscous and capillary forces, whose relative effects have to be estimated.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A4-1) What triggers liquid-vapour interface instabilities? **Priority: 2** **Significant progress expected by 2024**	Larger length scales and absence of buoyancy	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Evaporation Patterns (CIMEX), Thermal Platform inserts (Drop Evaporation, Self-rewetting Fluid, Enhanced Evaporators, Marangoni in Films, Shear Driven Film) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, In-Orbit Fluid Managements); boiling crisis research within DECLIC programme	Gravity generally has a marked stabilising or destabilising effect under terrestrial configurations. In order to be able to precisely reveal the contribution of other forces, sometimes much smaller than gravity in terrestrial configurations, in a number of cases this needs to be assessed in weightlessness. Among the reference experiments the interfacial temperature discontinuities and the interfacial energy transport would also need to be addressed.
A4-2) How do interface instabilities lead to breakup? **Priority: 3** **Significant progress expected by 2020**	Larger length scales and absence of buoyancy	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Thermal Platform inserts (Self-rewetting Fluid, Enhanced Evaporators, Marangoni in Films, Shear Driven Film) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, In-Orbit Fluid Managements)	Breakup itself is a predominantly capillary-driven process also under terrestrial conditions. Thus, its physics should be studied on ground. However, instabilities leading to breakup may be the subject of investigations in weightlessness, where the boundary conditions justify this. Tests of real or model heat transfer systems for instance would highly benefit from in-situ test conditions (see also the aspect of flow regime).

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A4-3) How does interface instability influence heat transfer characteristics? **Priority: 2** **Significant progress expected by 2024**	Larger length scales and absence of buoyancy	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Evaporation Patterns (CIMEX), Thermal Platform inserts (Drop Evaporation, Self-rewetting Fluid, Enhanced Evaporators, Marangoni in Films, Shear Driven Film) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, In-Orbit Fluid Managements); boiling crisis research within DECLIC programme	A number of cases studied in weightlessness without the influence of buoyancy and hydrostatic pressure could lead to the refinement and validation of models describing the contribution of other processes, which are not influenced by gravity.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A5-1) How to predict the local concentration of volatile components in a mixture at a liquid-vapour interface? **Priority: 3** **Significant progress expected by 2024**	Absence of buoyant convection	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Evaporation Patterns (CIMEX), Thermal Platform inserts (Boiling, Drop Evaporation, Marangoni in Films, Shear Driven Film, Self-rewetting Fluid) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, In-Orbit Fluid Managements, Pulsating Heat Pipe	In order to predict the local concentration of volatile components in a mixture all the different aspects that affect the physical process should be carefully taken into account. Microgravity offers the opportunity to avoid gravity (buoyancy) effects which greatly affects the liquid-vapour interface and therefore the local concentration of the volatile components. During long-duration microgravity, flow pattern visualization and concentration measurements can be performed. These important results with the experiment performed on ground will be the baseline for the comprehension of the process and its modelling.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A5-2) What is the impact of a discrete phase (e.g. particles) in the bulk fluid and at the interfaces? **Priority: 4** **Significant progress expected by 2024**	Larger length scales and change of interface shape	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Thermal Platform insert (Boiling, Drop Evaporation) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Boiling & Flow Boiling, Spray Cooling in Space	When studying the impact of a discrete phase dispersed in a base fluid, gravity plays an important role for both bulk and interfacial phenomena. In the bulk, the influence of density mismatching between particles and base fluid is clearly significant and entrain flotation or sedimentation phenomena. For submicron particles, however stabilized, the presence of a gravity field has an impact, sometimes relevant, on the aggregation kinetics. , In the latter case microgravity can allow a purely diffusive regime to exist and a more controllable evolution of the self-assembled aggregates. At the interface, for both micron and submicron particles, complex interaction of various processes occur. By studying these processes in microgravity, the impact of the interfacial distribution of the dispersed phase is magnified. Such an assessment, can help to understand the fundamental processes of particle assembly induced by capillary forces and also pave the way for enhanced technologies in both heat and mass transfer and photonics, among others.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A5-3) What is the effect of non-condensable gases? **Priority: 3** **Significant progress expected by 2024**	Isolating dominant effect of Marangoni convection	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Evaporation Patterns (CIMEX), Thermal Platform inserts (Boiling, Drop Evaporation, Marangoni in Films, Shear Driven Film, Self-rewetting Fluid) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Spray Cooling in Space	Non-condensable gases have an impact on the total pressure in gas-liquid phase change systems. Via local saturation conditions they contribute to the onset of thermocapillary convections and in certain cases also trigger solutal interfacial instabilities. Microgravity investigations in the absence of buoyancy-driven processes in a number of key configurations may allow the underlying mechanisms to be precisely determined.
A5-4) What is the impact of additives/surfactants at quasi-static and dynamic interfaces? **Priority: 5** **Significant progress expected by 2024**	Isolating dominant effect of Marangoni convection	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Thermal Platform insert (Marangoni in Films) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Spray Cooling in Space	When focusing on interfacial phenomena, minimising the coupling with buoyancy-driven processes (in regimes which would otherwise be affected by gravity) gives a better insight into capillary- and diffusion-driven phenomena. Thus, experiments in a number of configurations in weightlessness are recommended.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A5-5) How to predict heat transfer properties in emulsions? **Priority: 5** **Significant progress expected by 2024**	Isolating dominant effect of Marangoni convection and nucleation phenomena	droplet freezing nucleation Marangoni stress	FASES (Fundamental and Applied Studies in Emulsion Stability)	Absence of buoyancy contributions will prevent sedimentation/creaming of emulsions. Weightlessness is therefore required to provide access to thermocapillary migration of the droplets and description of droplet freezing/melting when applying cooling/heating temperature ramps to the emulsions.
B1-1) What are the dominant mechanisms and parameters of heterogeneous nucleation? **Priority: 4** **Significant progress expected by 2024**	Absence of buoyant natural convection	pool boiling, flow boiling, drop-wise condensation, flow condensation	None	This activity is very relevant to microgravity but in an indirect way. The outcome here is to identify the impact on the boundary conditions for the study. As such, predominantly terrestrial studies are recommended. Nevertheless, data from space experiments driven by other objectives would contribute to the relevant database, as they may constitute a better defined/described boundary condition.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
B1-2) How can nucleation site activation and active site density be predicted? **Priority: 4** **Significant progress expected by 2024**	Predictable thermal boundary layer growth	pool boiling, flow boiling, drop-wise condensation, flow condensation	None	Considering the scales involved, at the time of preparing the present document the relevance of microgravity conditions is not identified beyond impacting on the boundary condition. Thus, predominantly terrestrial studies are recommended.
B2-1) How can the influence of different parameters on wettability be predicted? **Priority: 3** **Significant progress expected by 2024**	Enlarged length scales	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	Thermal Platform inserts (Boiling, Drop Evaporation, Enhanced Evaporators, Marangoni in Films, Shear Driven Film, In-Tube Condensation) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Spray Cooling in Space	The bulk of the relevant studies should be performed on ground. However, configurations relevant for space-based systems (propellant tanks in ballistic phases, thermal management devices, etc.) or some reference cases in the absence of processes occurring on ground (gravity-driven drainage, etc.) should be assessed in weightlessness. At the conception and analysis of experiments focus should also be on the evaluation of the adsorption isotherms at pressures above the saturation-vapour pressure.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
B2-2) How does the wettability influence contact line dynamics? **Priority: 2** **Significant progress expected by 2020**	Enlarged length scale	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	Thermal Platform inserts (Boiling, Drop Evaporation, Enhanced Evaporators, Marangoni in Films, Shear Driven Film, In-Tube Condensation) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Spray Cooling in Space	The fundamental aspects of the question (which occur at small scales) should be addressed on ground. However, for large-scale processes, it is gravity that tends to dominate, rendering the observation of the role of the capillary phenomena and wettability more problematic. On the other hand, certain configurations, in particular those relevant for space based systems, need to be tested in weightlessness. Furthermore, experiments performed in a simpler (microgravity) environment may feed valuable reference data into terrestrial studies and in particular to theoretical/ numerical models.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
B3-1) What are the dominant heat transfer mechanisms (contact line, microlayer, transient conduction) under various circumstances (fluid, wall and process parameters)? **Priority: 1** **Significant progress expected by 2020**	Absence of buoyant natural convection and larger length scales	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	BXF/MABE, BXF/NPBX, Flow Boiling and Condensation Experiment (FBCE), Boiling Two-Phase Flow Experiment (TPF), Multiscale Boiling (RUBI), Evaporation Patterns (CIMEX), Thermal Platform inserts (Boiling, Flow Boiling, In-Tube Condensation, Drop Evaporation, Pulsating Heat Pipes, Enhanced Evaporators) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, In-Orbit Fluid Managements, Pulsating Heat Pipe, Two-phase Flow Loop in Space, Spray Cooling in Space; boiling crisis research within DECLIC programme	Certain processes in moderately complex configurations (e.g. nucleate boiling, drop-wise condensation) have an associated spatial and temporal scale, which makes it difficult to study the contribution of various underlying thermodynamic phenomena. Therefore, it is important to perform benchmark experiments in microgravity. On the one hand, this generally gives access to a more careful observation of the phenomena, at greater spatial and temporal scales without being disturbed by gravity. On the other hand, as this is carried out in a well-defined and relatively simple environment (in microgravity conditions), it eases the general understanding as well as the consequent model development and provides a basis for validation.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
B3-2) How does local heat transfer influence wetting characteristics and vice versa? **Priority: 1** **Significant progress expected by 2020**	Larger length scales	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	Multiscale Boiling (RUBI), Thermal Platform inserts (Boiling, Drop Evaporation, Self-rewetting Fluid, Enhanced Evaporators, Shear Driven Film, In-Tube Condensation) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Spray Cooling in Space; boiling crisis research within DECLIC programme	Determining precisely the local heat transfer for instance near a moving contact line is highly challenging on ground due to the involved spatio-temporal scales and the variety of involved processes (driven e.g. by capillarity, buoyancy).Therefore, ground-based investigations would highly benefit from a number of cases performed in weightlessness.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
B4-1) How does particle adsorption influence nucleation? **Priority: 5** **Significant progress expected by 2024**	Larger length scales	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	None	Although the majority of fundamental studies can be performed on ground, due to the distinct behaviour of the thermal boundary layer in weightlessness, linked to existing adequate experiment opportunities and relevant regimes, particle adsorption-induced nucleation could be assessed in microgravity creating benchmark cases.
B4-2) How does adsorption influence wetting characteristics? **Priority: 5** **Significant progress expected by 2024**	Larger length scales	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	Thermal Platform insert (Drop Evaporation) TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation	The impact of particle and/or fluid adsorption on wetting should be predominantly studied on ground. However, if benchmark experimental data can be achieved from space experiments without substantial additional efforts, the objectives should be considered, especially in the presence of phase change phenomena.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
B4-3) How to predict adsorption and energy transport across an adsorbed film? **Priority: 5** **Significant progress expected by 2024**	Larger length scales, absence of buoyant natural convection	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	Thermal Platform insert (Drop Evaporation) TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation	The development of relevant models should be carried out by relying on ground-based studies. However, their validation should be aided with data in weightlessness, especially for diffusion limited phase change phenomena.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
B4-4) What is the influence of heat transfer on desorption properties and chemical alteration of porous materials? **Priority: 5** **Significant progress expected by 2024**	Larger length scales, absence of natural convection	pool boiling wetting	Post-MATRA (Mass Transfer Analyser)	Porous substrates have specific structures that involve strong capillary effects when interacting with a liquid. They can be moreover chemically modified when submitted to temperature constraints. One consequence of this is the possibility for porous substrates to desorb important amounts of gas into the liquid phase. This will modify their overall heat and mass transfer properties. Transfer properties are actually strongly affected by the hydrodynamics inside the liquid phase and at the liquid/porous substrate interface. In weightlessness, buoyant natural convection is suppressed. Such conditions can therefore help to bring new insights into the understanding of the interplay between capillary- and diffusion-driven phenomena.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
C1-1) What is the influence of the thermal characteristics of the wall material on the conjugate solid-fluid heat transfer? **Priority: 1** **Significant progress expected by 2020**	Longer time scales	pool boiling, flow boiling, film evaporation, drop evaporation, drop-wise condensation, flow condensation, film condensation, heat pipes	Multiscale Boiling (RUBI), Thermal Platform inserts (Boiling, Drop Evaporation, Shear Driven Film) SOBER-SJ10(Single bubble pool Boiling Experiment aboard SJ-10) EFILE/SJ10: Drop Evaporation in Space Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Spray Cooling in Space; boiling crisis research within DECLIC programme	In weightlessness the characteristic time scales associated with dynamic and thermodynamic processes of phase change phenomena (in relevant regimes) can be matched, allowing the definition of benchmark cases to be used for the better understanding of the importance of the wall material thermal characteristics. Therefore, reference cases are suggested to be performed in a microgravity environment.
C2-1) What is the effect of substrate geometry and size (mini- and microscale) on the liquid-vapour interface? **Priority: 1** **Significant progress expected by2024**	Larger length scales	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	BXF/MABE Thermal Platform insert (Shear Driven Film) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Spray Cooling in Space	The governing processes of phase change phenomena in weightlessness are different from those dominating on ground. Thus, in order to develop and validate the influence of the wall geometry and size, benchmark cases are needed in microgravity conditions. However, the associated objectives can and should, by definition, be combined with other objectives.

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
C3-1) What is the effect of thermal surface topography/ chemistry on liquid-vapour interface dynamics? **Priority: 2** **Significant progress expected by 2024**	Buoyancy-driven interface deformation	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	Thermal Platform inserts (Boiling, Drop Evaporation, Condensation on Fins, Enhanced Evaporators, Marangoni in Films, Shear Driven Film) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Spray Cooling in Space	The time scales and the governing processes in weightlessness are different from those dominating on ground, in particular for phase change phenomena. Therefore, in order to develop and validate relevant models, a number of benchmark cases are needed in microgravity conditions.
C3-2) Can the surface topography/chemistry be used/designed to enhance heat transfer? **Priority: 1** **Significant progress expected by 2020**	Larger length scales, stable stratification	pool boiling, flow boiling, drop evaporation, drop-wise condensation, flow condensation, heat pipes	Thermal Platform inserts (Boiling, Drop Evaporation, Condensation on Fins, Enhanced Evaporators, Marangoni in Films, Shear Driven Film, In-Tube Condensation Self-rewetting Fluid) Two-phase Fluid System in Space/TZ-1: Film Evaporation & Condensation in Space; TPhasER/CSS (Two Phase System Experimental Rack on the Chinese Space Station): Evaporation, Condensation, Enhance Phase-change Heat Transfer, Boiling & Flow Boiling, Spray Cooling in Space	In particular in relation to technologies relevant for space missions it is important to validate modelling and design tools via microgravity studies in order to be able to conceive reliable heat transfer systems.

This table should not to be seen as an exhaustive list of scientific objectives of two-phase heat transfer research. Instead, it represents a "snapshot" of the main fundamental scientific questions that scientists face at the time of the preparation of the present issue of this document. As it is the nature of research, some questions might be answered in the near future, while new questions might arise.

3.4. Industrial Partnerships in Europe and Industrial Benefits

Some industries participating in the Microgravity Application Programme projects (i.e. MAP Heat Pipes, Evaporation, Condensation and Boiling) are involved in research, development and manufacturing of advanced heat transfer devices and thermal systems, and are interested in solving thermal management problems both for ground and for space applications. Their interests are focused on innovative heat transfer systems with enhanced performance, compactness, intelligence and reliability. These systems may use advanced working fluids, materials, surface structures, optimized geometries and new multiphysics approaches such as magnetic and electric fields, for example. The innovation drivers are footed in the advancement of two-phase heat transfer technology to becoming as high technology as the devices they are heating or cooling. Some examples of European Industrial entities and their focus are given below in order to give a sense of the relevance of the proposed research to industry:

- AAVID Thermalloy: AAVID has been a world leader in thermal management solutions for half a century. With heat management being one of the most crucial aspects of electronics packaging, from both performance and reliability standpoints, they are continually interested in new concepts, technologies and approaches for thermal energy management in order to keep the pace with electronic device technology advancement. An example is a novel concept for a multi-evaporator loop thermosyphon which is currently under development.
- Euro Heat Pipes: EHP is the European leader in space thermal control systems based on the use of two-phase systems, with more than 30 years of in-orbit heritage. In this context they are focused on the science of heat pipes and the development of technologies that enhance performance, reduce size and/or weight, and ensure controllability, among many other aspects. In this context, EHP are keenly interested in current progress on two-phase heat and mass transfer research on topics including, though not limited to, those associated with solid metal and working fluid interactions i.e. enhanced boiling surfaces, (onset of nucleate boiling, nucleation site density); the influence of wettability and/or porosity; enhanced surface topologies (wickability, multi-scale surfaces, optimized surfaces) and so on.

In the framework of the Heat Pipes project, in addition to the interaction with large industry, there are many small- and medium-sized enterprises that have a vested interest in two-phase flow and heat transfer science and technologies, ranging from the development of diagnostic systems to advanced cooling or heating devices. Examples of SMEs include, though are not limited to, Argotec, PROMETE and Techno System Development.

To highlight another field of the community, research on film-wise and dropwise condensation will have direct and indirect impact for the European industries. The companies involved in the experiments on condensation are directly interested in the development of new heat exchangers, novel surface treatments/coatings for dropwise condensation, novel heat pipe designs, etc. They cover industrial applications in the domains of aerospace and material science.

Beyond delivering unique knowledge, the proposed space experiments and the associated ground-based studies stimulate new ideas and concepts for companies. This is particularly true nowadays for dropwise condensation, which may allow a breakthrough by capitalising on the advancements in material engineering. As an example, 3D surface patterning can have tremendous potential in biotechnology, biodetection and in microelectronics applications.

Also of particular importance in condensation studies are passive heat transfer systems, which need careful design due to the several competing underlying forces.

Present studies of condensation, both film-wise and dropwise, will lead to optimised designs of equipment to save energy or to produce drinkable water in extreme conditions. This is of utmost importance in our current environment. Many European companies dealing with these kinds of markets will find opportunities for new developments.
As far as evaporation is concerned, active research is still ongoing nowadays concerning the contribution of liquid flows to the overall evaporation rate, hence to the performance of devices based on liquid/vapour phase change. Such flows

may be buoyancy-driven (on earth), or surface-tension-driven (both on earth and in space), and are highly dependent on the geometry of the evaporator. Moreover, all two-phase heat transfer devices necessarily involve triple (or contact) lines, where the liquid/vapour interface meets the solid heat conducting substrate. The optimization of the overall efficiency crucially depends on the understanding of near-contact-line behaviour, and on our ability to quantify how much such small-scale effects contribute to the overall performance. This concerns cooling technologies such as heat pipes, boiling, or spray cooling, for instance, and several of the involved industries are currently interested in innovative types of solid substrates (chemically or mechanically treated) able to boost the rate of liquid-vapour phase change.

As condensation and evaporation, boiling is a very efficient way to transfer heat. Boiling can be promoted to enhance heat transfer. This is the case for instance in mechanically pumped loops, which will be used in future telecommunication satellites for cooling electronic components. Such loops are developed by Thales Alenia Space, partner of the Boiling project. Boiling can also be a drawback, for example in the tanks of the launchers where the vapour creation leads to an increase of tank pressure, triggering the release of propellant in case of long-duration missions. The study of heat and mass transfer in upper stage tanks is the object of a collaboration between Airbus Defence and Space and academic partners. In the frame of the Boiling project a common sounding rocket experiment was designed and performed to address this topic and collaborations on the basis of follow-up investigations (theoretical, numerical studies, etc.) are on-going.

Two-phase heat transfer research projects in microgravity are carried out by a network of internationally renowned investigators from numerous world-class universities and research centres alongside a diverse cross section of European industries with interests spanning within and beyond the state of the art of two-phase flow and heat transfer for both terrestrial and microgravity conditions. A balanced combination of partners together with coordinated team effort are bound to contribute to the efficient advancement and transfer of knowledge from research to industrial applications.

ROADMAP 4: ESA RESEARCH IN SPACE PROGRAMME MATERIALS SCIENCE ROADMAP

4.1. Introduction

Material scientists originally devoted most of their efforts to studying mechanical and physical properties related to microstructures. Then, engineering of the microstructures into products could eventually be achieved, sometimes requiring decades. The role of processing was very soon recognised as one of the main limiting steps in the design of products with the desired microstructure. In the last quarter century, based on new experimental and modelling techniques, a change in paradigm has taken place. The importance of the liquid-to-solid phase transformation has been illuminated. As one of the first forming steps in the processing route of materials, solidification from the melt leaves its fingerprints in the final products. Hence, it is of utmost importance to understand the properties of the molten state and its solidification behaviour in order to tailor the processing route and to achieve satisfying microstructures for in-use performance requirements.

One cornerstone of the current engineering projects related to solidification of materials is the modelling of cast parts (illustrated in Fig. 4.1) and semi-products (e.g., slab, billet, bloom, ingot): starting from the alloy selection to the casting design; the evolution of the solidification microstructure; and the subsequent mechanical forming steps and heat treatments to achieve optimum mechanical properties. Such an effort is based on three pillars:

- Understanding of the physical phenomena involved, from alloy thermodynamics, heat and mass transfers, to solid-liquid interface dynamics, and microstructure formation including defects;
- Development and refinement of computational tools;
- Materials properties databases, required for input parameters for understanding and modelling solidification processing.

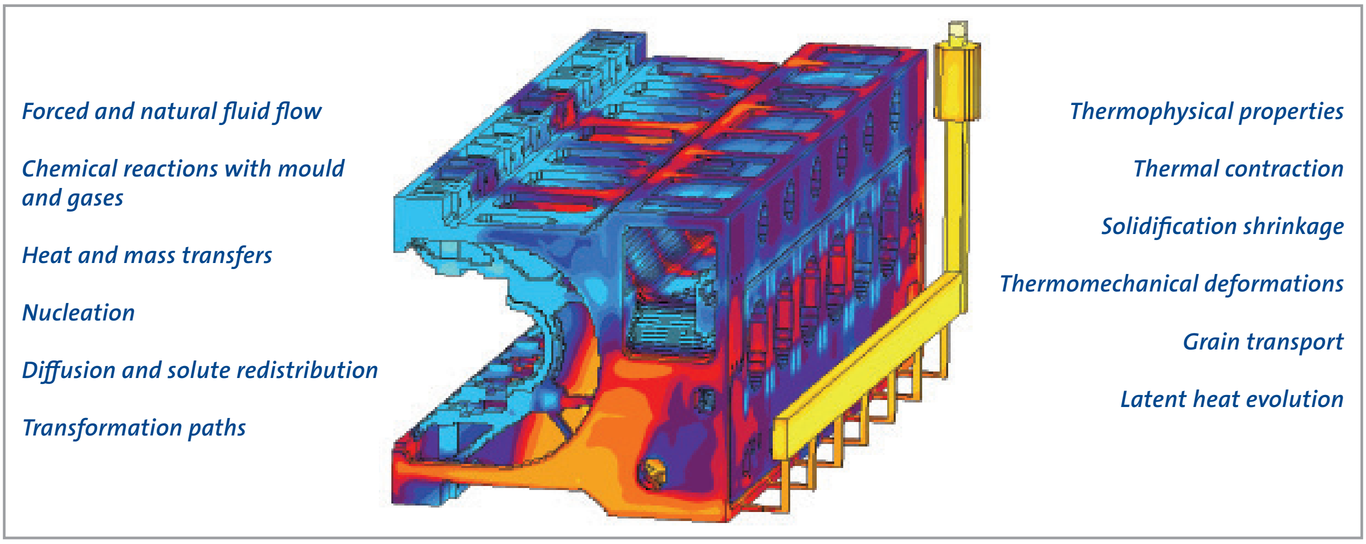

Figure 4.1. A wide but not exclusive range of fundamental aspects during casting of a complex component, here shown in relation to a temperature map predicted for car engine geometry.

Difficulties are linked to the variety of the length scales involved. For instance, length scales range from atomic (arrangement of atoms around the solid-liquid interface), to microscopic (spacing characterizing the microstructure), to mesoscopic (grain structure) and up to macroscopic (production scale).

The benefits of such an approach are manifold. On the casting side they include higher production efficiency, reduction of energy consumption and reduction of scrap material, in line with the recent Paris global accord on climate change to make manufacturing processes greener and more efficient. On the materials side it includes a reduction in weight through optimized casting and reduction of energy consumption through a reduced need for subsequent heat treatment. In general weight reduction implies the same or better mechanical properties at reduced weight. It results in less greenhouse gas emissions from transport as lower weight bears directly on reduced energy consumption. This issue covers the whole range from optimized casting techniques to tailoring of the solidification microstructure, combined with optimization of the alloy composition and development of new alloy compositions for a given application. The approach is relevant for all cast products and alloys, ranging from the automotive world, turbine blades for land-based energy production and jet engines, medical implants, large and small scale casting, and semi-finished products such as the continuous casting of slabs (90% of the 1.5 billion tonnes of steel cast in 2015!).

Microgravity experiments are particularly useful to achieve unique benchmark data to support the above efforts. The reduced gravity environment enables the control of experimental conditions to an extent impossible on Earth. The materials science community endorses the availability of various platforms with different microgravity durations, including drop-towers, parabolic flights, sounding rockets, the International Space Station (ISS) and eventually also research satellites. The rich experience gained from more than 30 years of materials science research in microgravity allows the definition and realization of dedicated experiments with significant return to society.

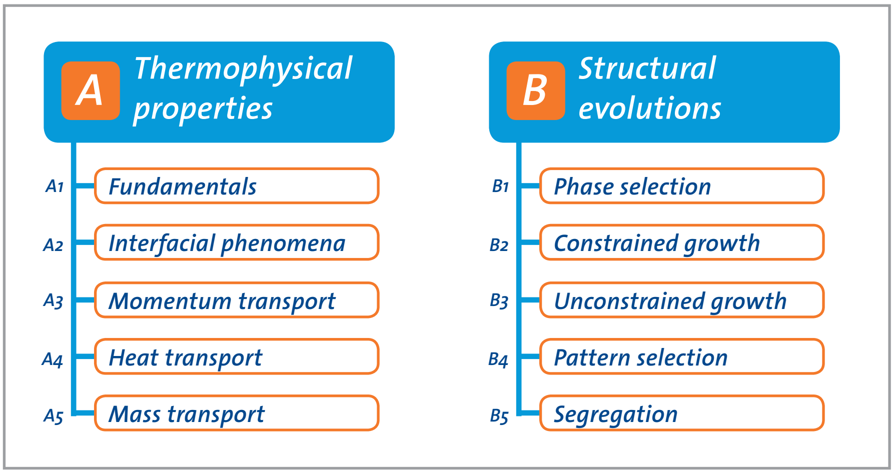

Figure 4.2. Physical phenomena from processing and properties to solidification microstructure in materials.

4.2. Categorization of Research Topics

In order to produce materials that meet ever higher specific requirements and performance, the solidification processing of structural and functional materials has to be controlled with ever increasing precision. It is foreseen that the materials of tomorrow will be optimised in their design, underpinning more efficient production conditions, optimizing utilization of scare resources and favouring cleaner processes. The two major research areas (Figure 4.2) at the heart of this roadmap covering the breadth of materials science research under microgravity conditions on a European scale are:

A. the reliable determination of the thermophysical properties of metallic melts for industrial process design,
B. the structural evolutions of materials, which require the reliable determination of the formation and selection mechanisms at microstructure scales in order to develop new materials, products and processes.

These two major research areas are equally key areas highlighted in the long-term US Materials Genome Initiative as well as the Metallurgy Europe programme as discussed in their respective white papers. The relevant physical phenomena underlying both research areas are listed in Figure 4.2 and in more detail in the figures and tables elaborated in this section hereafter.

4.3. Open Scientific Questions

Progress in understanding structural evolutions upon solidification requires precise knowledge of the thermophysical properties of the melt, thus justifying the structure of the present roadmap summarized in Figure 4.2. Hereafter, Figures 4.3 and 4.4 provide a global overview on currently open scientific questions for the research areas covered by the present roadmap. Each question is developed in Tables 4.1 and 4.2, together with arguments for microgravity relevance.

4.3.1. Thermophysical Properties of Liquids

For the continued improvement of materials processing with increasing requirements on composition, microstructure and behaviour in use - which often implies the breaking of technology barriers - the reliable and accurate knowledge of the relevant thermophysical properties of high-temperature melts is necessary. Thermophysical properties are required as input parameters for adequately describing balance in volume phases (heat, chemical species, momentum...) and at boundaries (solid-liquid, liquid-gas ...) that together form a set of coupled equations as a basis for modelling and numerical simulations.

The paucity of thermophysical property data in the liquid state for commercial materials as well as materials of fundamental interest is a result of the experimental difficulties generally arising due to high temperatures and/or gravitational forces. Some of these data can be obtained more or less accurately by conventional methods, in particular for non-reactive metals such as noble metals and non-metals. However, high precision measurements of thermophysical properties detailed in (A1-A4) on chemically highly reactive metallic melts at the temperatures of interest require the application of containerless processing techniques and the use of high-precision 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 becomes possible. For highly reactive metallic melts, ElectroMagnetic Levitation (EML) is a well-developed containerless technique. Ground-based experiments have achieved limited success due to the strong electromagnetic fields perturbing the measurements through excessive sample heating, strong and turbulent fluid-flow, sample deformation from an ideal spherical shape and in-homogeneous magnetic fields. With much smaller levitation forces required, benchmark experiments are readily motivated. In the past this technique has repeatedly and successfully been used in parabolic flights and aboard the TEXUS sounding rocket already leading to answers in some aspects. However, microgravity times are far too short to reach thermal equilibrium and measurements in the adiabatic regime. Expanding the experimental time – temperature window through the use of the EML facility installed in the European Drawer Rack of Columbus on board the ISS will open a completely new realm of space experimentation.

Mass transport impacts on the formation and evolution of microstructures during solidification. Measurements in the area of mass transport - diffusive and thermal - (A5) are hampered on ground by buoyancy convection. In recent years conventional furnace techniques used in the past have been further developed. In particular, applying real-time diagnostic means by radiographic techniques to in-situ experiments has provided a major step forward in this area and led to a new precision in the acquired data. A very limited number of benchmark experiments on chemical and self-diffusion in liquid metal alloys have been carried out aboard the sounding rocket (MAXUS) and shear-cells aboard the Foton satellite. In the future experiments could benefit from long-duration experiments aboard the ISS in suitable diagnostic inserts and cartridges in the Materials Science Laboratory (MSL).

Sophisticated methods of controlled levitation, magnetic excitations of surface oscillations, radio frequency power modulation, optical and temperature diagnostics, impedance change of pickup coil, in-time control and data analyses are available for these investigations. The direct measurement of surface and volume dependent thermophysical properties of metallic melts in the range between 700 and 2200 °C can thus be fully exploited on short and long time scales. Besides answering fundamental questions (A1), several issues will be addressed in detail using the following methods:

- (A2) Interfacial Phenomena. The oscillating drop technique measures surface tension as a function of temperature and undercooling.
- (A3) Momentum Transport. Videographic techniques are used to measure density, coefficient of thermal expansion (A3-R1) and viscosity (damping characteristics of surface oscillations) (A3-V).
- (A4) Heat Transport. Alternating Current (AC) modulation calorimetry measuring internal and external relaxation times provides specific heat, thermal conductivity and total hemispherical emissivity in the stable and undercooled liquid regime, as well as enthalpies, entropies and Gibbs free energies by integration of heat capacity data (A4-C1, A4-K1). Electrical conductivity is measured by impedance change of pick-up coil (A4-E).
- (A5) Mass Transport. In-situ real-time determination by X-ray radiography on binary liquid samples processed in suitable furnaces can be used for chemical diffusion (A5-D) and thermal mass transport (A5-L). Self-diffusion by combination experiments (A5-A) and chemical diffusion in ternary and multicomponent alloys (A5-D) is based on shear-cells in an isothermal field in a suitable furnace.

4.3.2. Structural Evolutions from Liquids

Physical phenomena taking place upon melt solidification are numerous. However, their individual study is often made impossible due to their complex interplay. Microgravity provides the unique opportunity to suppress the effects of gravity and in particular "naturally"-driven convection due to buoyant motions of the liquid phase and of solid particles in bulk samples. This is of course not so simple, as other sources of phase motion remain present in microgravity, e.g. shrinkage-driven flow. However, their effect is much smaller in amplitude and carefully chosen set-ups can lead to almost pure-diffusion heat and mass transport regimes. Researchers can then focus sharply and exclusively on the complex remaining dynamics that lead, in a quiescent undercooled melt, to the selection of phases (B1) and patterns (B4) of the microstructures and its associated segregation (B5), for single solid phase growth and multiple solid phase growth, under constrained (B2) and unconstrained regimes (B3). Moreover, artificial convective transport can also be added, under full control by the experimenters, so as to analyse its effects on the physical phenomena. Such experiments in microgravity become benchmark data for theoretical and modelling studies, and part of more ample research work performed under controlled gravity- or terrestrial conditions. Indeed, all questions raised in Figure 4.4 and Table 2.2 target no liquid convection or controlled conditions for convective transport, together with the experimental techniques given hereafter.

- **Containerless solidification at high undercooling:** In situ realtime imaging of growth front with high speed camera, thermal analyses, adjustable convection, undercooling statistics, metallurgical inspections (metallography, electron microscopy, composition analyses, ...). Studies on the initial melt transformation include nucleation (B1-N) and demixing (B1-D). They mainly determine initial phase selection during solidification and obviously demonstrate collaborations with the 'Thermophysical properties' area as the theme of research is closely related to melt properties. Containerless processing is also present in studies related to unconstrained rapid solidification from undercooled melts (B3-KU1), the amount of microstructures and phases in alloy solidification (B5-SP) and the effect of density variations between phases at the origin of shrinkage, porosity (B5-S) and thermomechanical deformations (B5-T), all taking advantage of the in situ diagnostics using highspeed video imaging of the growth front and the entire sample as well as cooling history.

- **Solidification at low undercooling with controlled temperature gradient:** Insitu realtime imaging of growth front with x-ray in metallic systems and with light optical observation in transparent organic model alloys, adjustable convection, adjustable temperature gradient and withdrawal rate, thermal analyses, metallurgical inspections (metallography, electron microscopy, composition analyses, ...). Larger time and length scales phenomena are usually investigated by directional solidification experiments, hardly tackled by parabolic flight and sounding rockets, and thus requiring access to the ISS. They mainly rely on apparatus in the MSL, such as the Low Gradient Furnace (LGF) or the Solidification Quenching Furnace (SQF), possibly coupled with triggered convection using magnetic fields. Benchmark experiments are then targeted for the growth kinetics and pattern selection during growth of a single solid phase (B2-KC, B4-DG) and multiple solid phases (B4-PG, B4-EG), or on transition in grain structure morphology (B3-EQ2, B3-EQ3). In-situ real-time observations are also developed for directional solidification and/or low undercooling and temperature gradients. While obvious for transparent alloys using the so-called "MSGTransparent" facility, it is also planned for metallic alloys, taking advantage of x-ray imaging so far exclusively used on sounding rockets (MASER, MAXUS) and in parabolic flights. The dynamic of structural evolutions will provide data for growth competitions among columnar structures (B2-C1), fragmentation of a preexisting dendritic microstructure (B2-F), and growth kinetics (B3-KU2) and morphology of equiaxed grains (B3-EQ1).

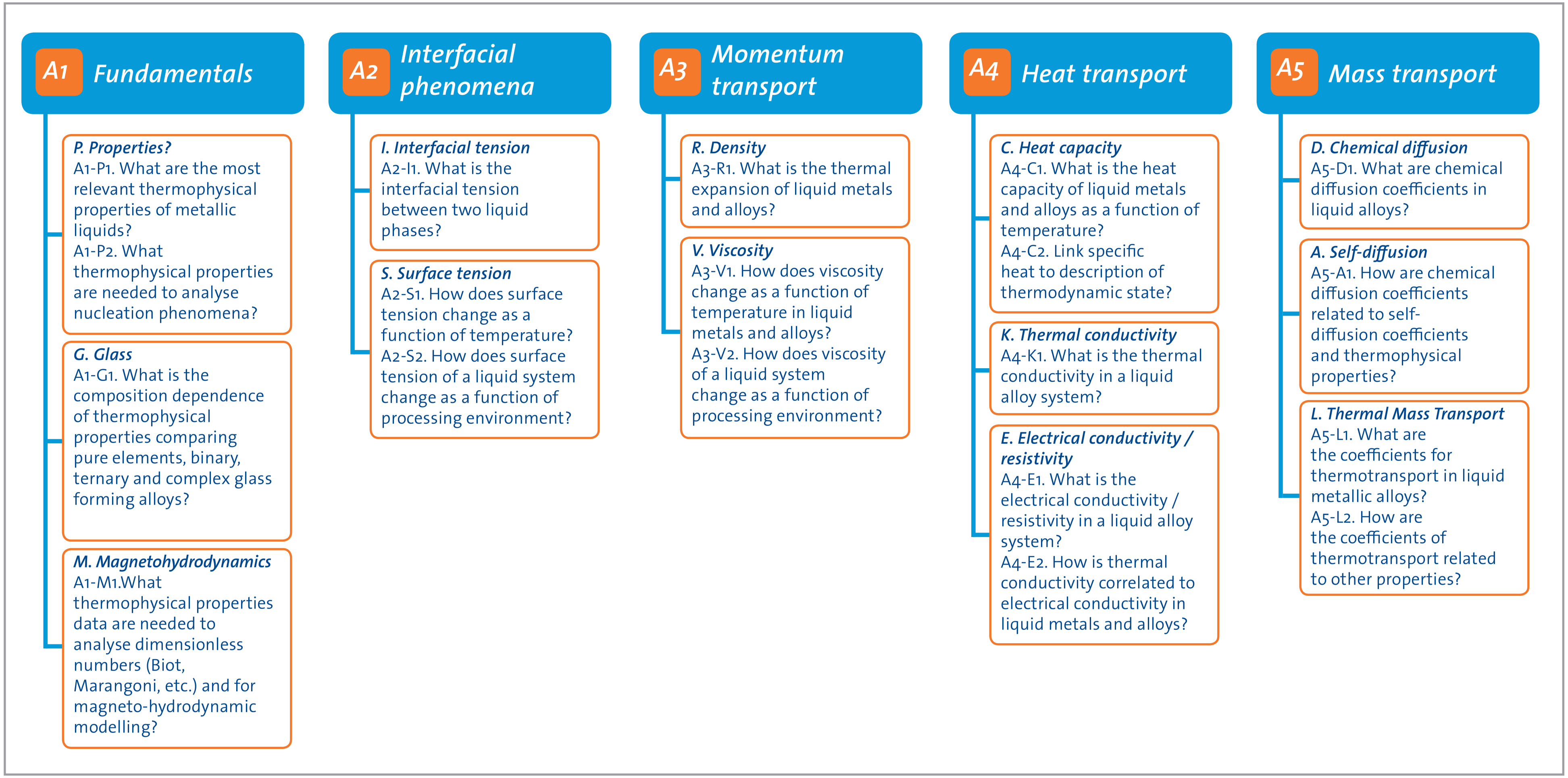

Figure 4.3. Scientific Topics in the Area of Thermophysical Properties of Liquids to be Addressed in Microgravity Experiments.

B1 Phase selection

N. Nucleation
B1-N1. How does nucleation depend on convection in liquid metals and alloys?

D. Demixing
B1-D1. What are the physical phenomena behind liquid phase separation or is demixing in microgravity solely controlled by the liquid-liquid interfacial energy?

B2 Constrained growth

KC. Kinetics
B2-KC1. How does dendritic growth kinetics depend on melt convection upon directional solidification?

C. Competition
B2-C1. Is our understanding for growth competition between arrays of cells / dendrites / columnar grains correct?

F. Fragmentation
B2-F1. What are the mechanisms and kinetics for the formation of fragments from a pre-existing dendritic solid structure?
B2-F2. What are the parameters influencing the fragmentation mechanisms and seeding of the melt?

B3 Unconstrained growth

KU. Kinetics
B3-KU1. How does dendritic growth kinetics depend on melt convection upon rapid solidification in highly undercooled melt?
B3-KU2. How does dendritic growth kinetics depend on melt convection upon equiaxed growth?

EQ. Equiaxed grains
B3-EQ1. What are the parameters influencing the globular-to-dendritic growth transition and inner grain structure upon unconstrained growth in alloys?
B3-EQ2. How does competition between grains proceed to create the columnar-to-equiaxed transition?
B3-EQ3. How do centrifugal forces impact on transition from columnar to equiaxed solidification?

B4 Pattern selection

DG. Dendritic growth
B4-DG1. How do interface stability and pattern selection depend on melt convection during directional solidification of a single solid phase?
B4-DG2. What are the interactions between ceramic particles and an advancing dendritic front?

PG. Peritectic growth
B4-PG1. How do bands and island patterns form?

EG. Eutectic growth
B4-EG1. What are the explanations for the formation of low symmetry patterns (lamella-to-rod transition) and coexistence of distinct patterns?
B4-EG2. What is the dynamic for two- and three-phase growth patterns in ternary or multicomponent alloys?

B5 Segregation

S. Shrinkage
B5-S1. What is the role of shrinkage on the redistribution of species?

SP. Solidification path
B5-SP1. What are the parameters that dictate the final fraction of microstructures and phases upon solidification of a melt?

T. Thermomechanics
B5-T1. What is the role of thermo-mechanical deformation of the solid phase on the redistribution of species and the creation of defects in the mushy zone?

Figure 4.4. Scientific topics in the area of Structural evolutions during solidification to be addressed in microgravity experiments.

Table 4.1: Scientific Questions for Thermophysical Properties of Liquids

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
A1-P1. What are the most relevant thermophysical properties of metallic liquids from a scientific point of view and from a technological point of view regarding numerical modelling?	Containerless electromagnetic processing of metallic liquids at elevated temperatures using MSL-EML on ISS in the European COLUMBUS module	Ability of fluids to flow and to form free surfaces; Liquid flow governed by Navier-Stokes equation; Fundamental modes of heat transfer, such as conduction or diffusion, convection and radiation	ThermoLab-ISS as a “science project”; ThermoProp as a “MAP project” (in combination THERMOLAB)	The relevance of space-research or microgravity lies in the possibility of studying liquid and solidifying molten metals, metallic alloys and semiconductors in the absence of convection and hydrostatic pressure. The higher atmospheric purity and lack of convection in the microgravity environment are essential to perform high precision containerless measurements on hot metallic melts. Each sample is suspended in weightlessness with only the support of magnetic repulsion. Next, the sample is liquefied by inductive heating. Several parameters can be measured at the same time on the liquid metal droplet as it levitates. No containers are used to hold the metals during experiments in the EML so that measurements of the heated metals can be taken in purest form. The main advantages of space experiments can be summarized as follows. • Avoidance of any chemical reactions with a metallic or ceramic container • Decoupling of electromagnetic heating and positioning fields and, therefore, minimised levitation forces and, thus, controlled heating and reduced liquid convection in comparison with 1g gravity conditions on earth • Achievement of fully spherical samples • Control of the sample environment (and cooling rate) in vacuum (better than 10^{-8} Torr) or inert gas atmosphere • Extended periods of processing time (> 10,000 sec.) in a temperature range between 700 and 2200 °C and, thus, • Considerably improved accuracy of the measurements. *Measurements to be performed by high resolution pyrometer and two high speed video cameras (side view, top view); extended duration of ISS experiments; medium to short-duration experiments sounding rockets and parabolic flights.*

A1-P2. What thermophysical properties are needed to analyse nucleation phenomena in general and with regard to question B1-N1?	See B1-N1	Classical and transient nucleation theory	ThermoLab-ISS; ThermoProp	During processing from the melt (e.g., casting, welding, single crystal growth and directional solidification), crystal nucleation and growth is in most situations the first step achieved by cooling of a liquid below its thermodynamic equilibrium solidification (liquidus) temperature to form crystalline nuclei of nanometer dimensions that subsequently start to grow. Alternatively, when the formation of nuclei fails, or the growth of nuclei is very sluggish, there is formation of a metallic glass at the glass transition temperature. The main limitations of fundamental understanding come from the lack of precise values of the thermophysical properties, in particular for the kinetic (viscosity, diffusion) and thermodynamic contributions (interfacial tension, Gibbs free energy). For pure elements such data do exist to some extent but for generally complex alloys used for engineering components they are basically unknown. It is concluded that the analysis of nucleation relies mostly on circular arguments since the basic thermophysical properties used in classical nucleation theory are generally unknown, in particular, for multi-component alloys thus requiring a quiescent space environment to obtain high precision data in the liquid state by eliminating gravitational effects.
A1-G1. What is the composition dependence of thermophysical properties comparing pure elements, binary, ternary and complex glass forming alloys?	Containerless electromagnetic processing; EML	Chemical ordering in the liquid; Thermodynamics	ThermoLab-ISS; ThermoProp	Bulk metallic glasses are emerging as important industrial materials. Recent studies indicate a nanoscale chemical segregation accompanying structural ordering in deeply supercooled Cu-Zr liquids near the optimum glass forming composition, and a density anomaly in the supercooled liquid of a $Zr_{58.5}Nb_{2.8}Cu_{15.6}Ni_{12.8}Al_{10.3}$ bulk glass that may reflect a fragile/strong transition. Strong resistance against crystal nucleation and growth are also found in multi-component systems with deep eutectics. By a variation in cooling rate and by different heat treatments the range of microstructural length scales can be varied by several orders of magnitude reaching from regular eutectic microstructures to the nanocrystalline and glassy state. Investigations to deepen our knowledge on bulk metallic glasses formation require convection free conditions.

A1-M1. What thermophysical properties data are needed to analyse dimensionless numbers (Biot, Marangoni, etc.) and for magneto-hydrodynamic modelling?	Containerless electromagnetic processing; EML	Fluid Physics; Data are basically unknown for metallic alloys at high temperatures	ThermoLab-ISS; ThermoProp	Heat and fluid transport in the liquid phase are generally described by dimensionless numbers such as the Biot, Marangoni, Prandtl, Rayleigh, Reynolds and Schmidt number (in alphabetical order) as well as the magnetic Reynolds number. These numbers allow a better categorization of phenomena, scaling of the system and thus a wider extrapolation of measurement results made on a particular system. The dimensionless numbers contain the basic physical properties of the system under consideration and are needed for heat and fluid flow calculations including a multitude of thermophysical properties required. In industrial technologies, process control becomes particularly important for the growth of single crystals and complex shapes. For example, in the aerospace and electric power industry the need for single-crystal turbine blades with enhanced thermal fatigue strength and creep resistance is obvious. However, the reproducibility of single-crystal growth of sufficiently large blades, in particular for stationary turbines is rather limited and needs improvement. Microgravity relevance as in A1-P1 - see above
A2-I1. What is the interfacial tension between two liquid phases?	Set of oscillating compound droplet data	Mass transport during coarsening of liquid droplets	COOLCOP; LIPHASE	Absence of sedimentation; extended duration of ISS experiments for enhanced demixing; convection control.

A2-S1. How does surface tension change as a function of temperature?	Oscillating drop technique	Atomistics of free liquid surface	THERMOLAB	Surface tension is the elastic tendency of fluid interfaces that makes them acquire the least surface area possible (mathematical proof is based on the Euler-Lagrange equation). In this case at liquid metal - gas interface, surface tension results from the greater attraction of metallic atoms (due to cohesion) than to the molecules in the atmosphere (due to adhesion). The net effect is an inward force at its surface that causes the liquid to behave as if its surface were covered with a stretched elastic membrane causing a “surface tension”. Surface tension thus is responsible for the shape of liquid droplets. Although easily deformed, droplets of liquid metals phenomenologically tend to be pulled into a spherical shape by the imbalance in cohesive forces of the surface layer. In the absence of other forces, including gravity, drops of virtually all liquids would be approximately spherical. This fact is used in the oscillating droplet experiments in space based on the surface oscillations triggered by controlled short magnetic field pulses. Surface tension is dependent on temperature. The general trend is that surface tension decreases with the increase of temperature, reaching a value of 0 at the critical temperature according to the Eötvös rule and related empirical equations.
A2-S2. How does surface tension of liquid systems change as a function of processing environment?	Oscillating drop technique	Adsorption layer on a free liquid surface; saturation coverage of the Langmuir model	OXYTHERM; THERMOLAB	Oxygen (and other elements such as nitrogen and sulphur in steel production) can drastically change thermophysical properties such as surface tension and viscosity. Thus, oxygen partial pressure needs to be controlled if benchmark data are to be measured on the ISS. OCS @ ISS will enable new scientific insights into oxidation/deoxidation mechanisms of liquid metals.
A3-R1. What are the thermal expansions of liquid metals and alloys?	Videographic technique	Anharmonicity of atomic vibrations in the liquid state	THERMOLAB	The thermal expansion and density changes as a function of temperature determine buoyancy-driven fluid flow effects and volume shrinkage during crystallization. As such, density change is one of the key parameters in numerical process simulations and needs to be known with utmost accuracy. Microgravity relevance is described in A1-P1 - see above

A3-V1. How does viscosity change as a function of temperature in liquid metals and alloys?	Developing a benchmark set of oscillating droplet data in the absence of external forces	Modelling of convection; Damping mechanisms; link to mass transport	THERMOLAB; PARSEC; COOLCOP; ICOPROSOL; LIPHASE; MAGNEPHASE	The viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. Viscosity is a property arising from collisions between neighbouring molecules / atoms in a fluid that are moving at different velocities. A pressure difference generally is needed to overcome the friction between particle layers to keep the fluid moving. Thus, a stress is required proportional to the fluid's viscosity (Newtonian flow). Zero viscosity is observed only at very low temperature in superfluids. Otherwise, all fluids have positive viscosity, and are technically said to be viscous with a distinct temperature dependence. Highly viscous liquids may appear to be solid (glass) when the viscosity values appear to be greater than about 1012 Pa sec. The measurement of viscosity in space is based on the oscillating drop technique (A2-S1) and the decay of surface oscillations as a function of time due to internal friction – a measure of viscosity – has been established. Obviously this thermophysical property is relevant for the analysis of solidification processes due to the distinctively different rheological behaviour of complex liquid alloy systems. Microgravity relevance is described in A1-P1 - see above
A3-V2. How does viscosity of liquid systems change as a function of processing environment?	Oscillating drop technique	Adsorption layer on a free liquid surface	THERMOLAB	Microgravity relevance is described in A1-P1 and A3-V1 - see above
A4-C1. What is the heat capacity of liquid metals and alloys as a function of temperature?	AC modulation calorimetry	Crystal-like clusters in the liquid state	THERMOLAB	Non-contact AC modulation calorimetry – as a new method for contact-free experimentation in space - is based on the sinusoidally modulated inductive heating power of a liquid metallic specimen and the high-presicion (< 0.1 K) measurement of the resulting temperature amplitude variation and its phase shift with respect to the heating power input. The first kind of such measurements was successfully performed in the IML-2 and MSL-1 Spacelab missions (Space Shuttle). In addition to specific heat the thermal conductivity in the liquid and total hemispherical emissivity (heat loss based on Stefan-Boltzmann's law) of a freely suspended liquid will be obtained as a function of temperature.

A4-C2. Link specific heat to descriptions of thermodynamic state?	AC modulation calorimetry	Synergy of thermophysical property measurements with computational thermodynamics	THERMOLAB; PARSEC	From the calorimetric data (obtained as per A4-C1), the enthalpy difference, the entropy difference and the Gibbs free energy difference between the undercooled liquid and the crystalline phase, and thus the (average) thermodynamic driving force for nucleation, will be evaluated. This can be considered as a critical test for classical homogeneous and heterogeneous nucleation theory where the interfacial between undercooled liquid and crystal to be formed is basically unknown but has to be considered.
A4-K1. What is the thermal conductivity in liquid alloy systems?	AC modulation calorimetry	Fourier law of thermal conductivity	THERMOLAB	In combination with magnetohydrodynamic modelling, this requires the absence of turbulence, and knowledge of the viscosity and electrical resistivity, all conditional on the prevalence of low microgravity levels.
A4-E1. What is the electrical conductivity / resistivity in liquid alloy systems?	Set of benchmark data under well defined experimental conditions (spherical sample in a homogeneous magnetic field)	Benchmark data for modelling of microstructure formation; chemical short-range order development in undercooled liquids; casting applications and crystal growth	Electrical-Resistivity	The temperature dependent electrical resistivity is important in many liquid metal processing operations because it controls the melt flow under the influence of electromagnetic fields. Electrical conductivity is also a sensible indicator for chemical short-range ordering in alloys increasing in the undercooled liquid state. For the investigation of hot reactive liquid metal alloys and in the undercooled state, electromagnetic levitation is the method of choice. For precise measurements external perturbing influences like sample deformation, strong-fluid flow, and convective gas cooling have to be reduced to a minimum and a homogenous magnetic-field is required, all of which can be achieved by performing experiments in microgravity. *Systematic real-time investigation in long-duration ISS experiments using electromagnetic levitator (EML) and sample coupling electronics (SCE). Absence of fluid flow; homogeneous magnetic field. Parabolic flights for particular samples possible.*

A4-E2. How is thermal conductivity correlated to electrical conductivity in metals and liquid alloys?	Comparison between AC calorimetry results and thermal conductivity calculated using the Wiedemann-Franz law from electrical resistivity	Casting applications and crystal growth	THERMOLAB; Electrical-Resistivity	The temperature dependent thermal conductivity is of fundamental importance in growth processes. The Wiedemann-Franz law relates thermal and electrical conductivity for pure liquid metals. For alloys the situation is less clear. By using electromagnetic levitation in microgravity both properties can be measured on the same sample with minimal external perturbations (absence of strong fluid-flow, sample deformation, convective cooling) and in a homogeneous magnetic field. In long-duration experiments a systematic approach to these quantities on the same sample is possible. *Systematic real-time investigation in long-duration ISS experiments using electromagnetic levitation (EML) and sample coupling electronics (SCE). Absence of fluid flow; homogeneous magnetic field*
A5-D1. What are chemical diffusion coefficients in liquid alloys?	Set of benchmark chemical diffusion coefficients under absence of fluid flow	Modelling of microstructure formation	GRADECET; DIFFSOL; SETA; XRMON; Binary alloys within XRMON: so far sounding rockets; future MSL-XRR* facility. Multicomponent alloys shear-cell setup: in the past FOTON; future ISS-MSL	In liquid alloys, diffusion impacts on the formation and evolution of microstructure during solidification. Diffusion coefficients are an important input parameter to microstructure modelling. For the liquid state the available databases are sparsely populated A major perturbing factor in experiments on earth is “natural” convection. Experiments in space provide data in the absence of buoyancydriven convection. For the more simple binary alloy systems, space experiments serve as a benchmark to improve ground-based measurements; and for higher component liquids, space experiments are required to provide accurate data. Accurate data can be obtained by in-situ experiments using X-ray radiography - so far carried out only on sounding rockets – for binary alloys and only by using shear-cells in isothermal furnaces for multicomponent alloys. For multicomponent alloys due to the absence of stable density layering (uphill diffusion) only microgravity experiments lead to accurate data. *Absence of buoyancy-driven convection. In-situ X-ray radiography observation of binary alloys; ternary and multicomponent alloys using shear-cells and post-mortem analysis; long-duration ISS experiments.*

A5-A1. How are chemical diffusion coefficients related to self-diffusion coefficients, thermodynamic data and other thermophysical properties?	Set of benchmark diffusion data and thermophysical property data under absence of fluid flow	Modelling of microstructure formation	XRMON; GRADECET; DIFFSOL; SETA; so far within XRMON on sounding rocket (MAXUS); future ISS MSL-XRR* facility. Multicomponent alloys shear-cell setup: in the past FOTON; future ISS-MSL; TT-TPP (viscosity)	Diffusion coefficients are an important input parameter to microstructure modelling. Due to inherent experimental difficulties it is often easier to measure other thermophysical properties on the ground, thereby deriving diffusion coefficients. However, underlying models linking diffusion to other thermophysical properties like viscosity and thermodynamic data are not well established for liquid alloys, whether they be binary or multicomponent. Diffusion in liquids is important from both an industrial point of view as well as in a fundamental science context by establishing the relation between different mass transport properties and the thermodynamic behaviour of systems. Experiments in microgravity enable the provision of a benchmark database linking self- and chemical diffusion with thermophysical properties and thermodynamic data. *Absence of buoyancy-driven convection. In-situ observation of diffusion binary alloys; ternary and multicomponent alloys using shear-cell and post-mortem analysis; long-duration experiments on ISS.*
A5-L1. What are coefficients for thermotransport in liquid metallic alloys?	Set of benchmark data in binary liquids under the absence of buoyancy convection	Modelling of microstructure formation	XRMON; within future ISS MSL-XRR* facility	Mass transport driven by thermal gradients (thermal transport or Soret effect) is of major interest, as these gradients are ubiquitous in solidification processes. The database for these transport properties compared with liquid diffusion data in metal alloy systems is even sparser. Existing models linking thermal transport to thermodynamic data await rigorous testing, and modelling approaches predicting data are in their infancy. At the moment there is no means to predict for a given material to which side – hot or cold – the heavier element diffuses. Therefore solutal destabilization makes measurements on ground impossible. Since concentration gradients need several hours to fully establish, measurements on long µg-time-offering platforms are a must. For precise measurements, in-situ radiographic techniques are required. *Absence of buoyancy-driven convection. In-situ observation of concentration evolution in a thermal gradient field using X-ray radiography; long duration ISS experiments.*

A5-L2. How are coefficients of thermotransport related to other properties?	Simultaneous measurement of chemical diffusion and thermal mass transport under absence of buoyancy convection.	Modelling of microstructure formation	XRMON; within future ISS MSL-XRR* facility	During metal alloy solidification both thermal as well as concentration gradients ahead of the growing solid-liquid interface are constantly evolving. In modelling of microstructure formation the respective transport coefficients are important input parameters. Thermal gradients are drivers of mass transport. Chemical diffusion and thermotransport are linked. Both types of experiment are severely affected on ground by convective flow. By carrying out long-duration experiments in µg, both transport properties can be simultaneously determined on the same sample using the real-time diagnostic technique of X-ray radiography. *Absence of buoyancy convection. In-situ observation of concentration evolution in a thermal gradient field; concentration evolution of a chemical gradient in a homogeneous thermal field; long-duration ISS experiments.*

Table 4.2: Scientific questions for Structural evolutions

Open fundamental scientific questions	Focus of space experiment(s)	Mechanisms involved / Relevant research topic	Related recent and future space experiment(s)	Comments on microgravity relevance
B1-N1. How does nucleation depend on convection in liquid metals and alloys?	Undercooling Statistics	Classical nucleation; Theory with extension to convective conditions; Particle fading	NEQUISOL; ICOPROSOL; PARSEC; MAGNEPHASE; COOLCOP; LIPHASE; XRMON	In most alloys, the chemical composition of the primary crystallizing phase differs from that of the undercooled liquid. The models for nucleation, link the attachment processes at the interface between the liquid and the new phase with the longer-ranged diffusion field resulting from the compositional differences. Predictions show that this can have a profound impact on crystal nucleation as well as on the subsequent crystal growth. However, convective stirring, which is dominant in terrestrial undercooling studies, makes it impossible to investigate this. Stirring could be sufficiently reduced under electromagnetic levitation studies carried out in microgravity conditions to reach nucleation in the diffusive regime. Moreover, by varying the fluid flow conditions systematic studies on the influence of fluid flow on crystal nucleation are possible. *Adjustable convection; extended duration of ISS experiments; medium to short-duration experiments sounding rockets and parabolic flights possible in certain areas.*

B1-D1. What are the physical phenomena behind liquid phase separation or is demixing in microgravity solely controlled by the liquid-liquid interfacial energy?	Distribution of liquid phases in the absence of buoyant natural convection	Liquid phase separation; Role of the liquid-liquid interfacial energy; Growth of liquid droplets in a liquid matrix; Coagulation; Sedimentation	COOLCOP (PF 2002-2008, TEXUS 44); LIPHASE (EML)	Liquid phase separation has only limited use in alloy design, because industrial alloy design needs safe process routines with well-known process parameters. Upon liquid-liquid demixing, a dispersion of liquid droplets develops driven by the interfacial energy between the liquids. The developing dispersion is subjected to convection in the melt, acceleration of droplet growth, collisions of droplets, coagulation and sedimentation. The microstructure of the finally solidified material is therefore the complex result of several interfering physical processes. It is the aim to identify the physical mechanisms behind liquid phase separation and growth, to evaluate their contributions and to model the resulting microstructure. Microgravity experiments give the unique opportunity to vary the convective level in the melt considerably. *Investigation of undercooled model systems with a metastable miscibility gap in EML; freezing of resulting liquid dispersion; metallographic inspection on ground after return of the samples to snapshot the evolution of liquid dispersions; experiments conducted under low convection.*
B2-KC1. How does dendritic growth kinetics depend on melt convection upon directional solidification?	Growth under well-defined fluid flow conditions	Growth kinetics; Modelling of microstructure evolution	MICAST; CETSOL; XRMON	One of the most challenging problems is the influence of convection during all stages of solidification. The interplay between an advancing solidification front and fluid flow in the molten alloy, although well known, still remains to be understood and carefully quantified, starting with the kinetics of a dendrite tip. *Adjustable convection from purely diffusive to controlled convective flow; long duration of ISS experiments.*

B2-C1. Is our understanding for growth competition between arrays of cells / dendrites / columnar grains correct?	Growth under diffusive and well-defined fluid flow conditions	Growth kinetics; Modelling of microstructure evolution; Growth competition within a single columnar grain; Growth competition between columnar grains	CETSOL; XRMON; MICAST	Upon constrained growth of a single solid phase from the melt, several microstructures can be observed depending on the solidification parameters (mainly alloy composition, temperature gradient, isotherm velocity, fluid flow). These are typically arrays of cells or dendrites originating from the same crystallographic orientation in case of single crystal growth. How these inner entities of a grain compete during growth is not well theoretically addressed. The presence of several grains (i.e., several arrays of cells or dendrites with different crystallographic orientations) is the general situation found in columnar zones of casting. How growth competition takes place at the grain boundaries is not well documented in a diffusive regime. Only recently modelling tools were made available for such studies. As convective flow changes the kinetics of each individual entity, interactions are first to be studied in a diffusive regime before taking into account the influence of adjustable convection. *Adjustable convection from purely diffusive to controlled convective flow by means of magnetic field stirring; long duration of ISS experiments.*
B2-F1. What are the mechanisms and kinetics for the formation of fragments from a pre-existing dendritic solid structure?	Fragmentation of a dendritic array under diffusive and well-defined fluid flow conditions	Fragmentation kinetics; Remelting; Mechanical breaking of a dendritic network	CETSOL; MICAST; XRMON	While there is no directly dedicated study on fragmentation of a pre-existing dendritic array, it is already observed in several experimental results carried out in microgravity conditions. Analyses of industrial processes also suggest fragmentation as the dominating source of equiaxed crystals in producing steel alloys or low angle grain boundaries in nickel base alloys. It is thus of primary importance to focus more on experiments aimed at understanding the physical phenomena leading to the detachment of a dendrite arm to form an isolated crystal from its mother dendrite. Mechanisms involved could be related to remelting and/or thermomechanical deformation of the dendrite arms. As remelting is a diffusion dominated phenomena, understanding requires damping the transport by convection to its minimum in the mushy zone, thus ISS experiments. *Adjustable convection during long duration ISS experiments.* *Macrosegregation or transient regimes in growth conditions leading to flow instability, plumes and chimney formation, dendrite detachment, freckles.*

B2-F2. What are the parameters influencing the fragmentation mechanisms and seeding of the melt?	Fragmentation of a dendritic array under diffusive and well-defined fluid flow conditions	Transport of the fragments; Seeding of the melt; Conditions for further growth of a transported fragment	CETSOL; MICAST; XRMON	For the fragments to serve as seeding of equiaxed grains, transport to the melt is required. It is believed that this is the result of liquid convection or buoyancy forces acting on fragments. For instance, freckle is a defect where small equiaxed grains are accumulated in a segregated channel formed as a result of the generation of fragments by thermosolutal convection, thus leading to macrosegregation. Systematic studies with well controlled conditions for convection starting with microgravity conditions with no forced convection, is required to evaluate the parameters influencing the formation of fragments upon directional solidification. *Adjustable convection during long duration ISS experiments.* *Macrosegregation or transient regimes in growth conditions leading to flow instability, plumes and chimney formation, dendrite detachment, freckles.*
B3-KU1. How do dendritic growth kinetics depend on melt convection upon rapid solidification in highly undercooled melts?	In-situ observation of growth front by high-speed video imaging	Growth kinetics; Modelling of microstructure evolution	NEQUISOL; ICOPROSOL; PARSEC; MAGNEPHASE; MULTIPHASE; CCEMLCC; COOLCOP; LIPHASE	Growth kinetics and microstructural evolution are dominated by heat and mass transport in the melt, which is not solely controlled by heat conduction and atomic diffusion but also by fluid flow. In industrial application metastable materials with novel properties are conventionally produced by methods of rapid quenching of the liquid such as melt spinning or inert gas atomization. Solidification of undercooled melts is an alternative method in order to obtain non-equilibrium solid phases. With the utilization of EML large undercooling levels prior to solidification can be realized even at slow cooling rates of bulk melts. This enables direct monitoring of rapid solidification, crystal nucleation and growth. Moreover, reduced gravity conditions offer the opportunity to control the level of electromagnetically-induced convection in order to study its effect on nucleation and growth phenomena. From microgravity experiments new experimental data for verification and refinement of physical models for growth kinetics and microstructure selection can be collected. *Adjustable convection; extended duration of ISS experiments.*

B3-KU2. How do dendritic growth kinetics depend on melt convection upon equiaxed growth?	Growth under well-defined fluid flow conditions	Growth kinetics; Modelling of microstructure evolution	MICAST; XRMON; CETSOL	Upon equiaxed solidification, at low undercooling, the main dendrite tip kinetics also dictate the growth kinetics of the grain envelope. As it is the result of heat and solute diffusion in the presence of fluid flow, systematic measurements are required to compare with existing theories and models. *Purely diffusive conditions. Controlled fluid-flow by magnetic field stirring; in-situ observation, parabolic flights, sounding rockets, long duration ISS experiments.*
B3-EQ1. What are the parameters influencing the globular-to-dendritic growth transition and inner grain structure upon unconstrained growth in alloys?	Growth under diffusive and well-defined fluid flow conditions; In-situ observation of equiaxed growth by X-Ray radiography	Growth kinetics; Modelling of microstructure evolution; Equiaxed growth; Grain interaction; Grain motion; Selection of crystallographic growth directions	XRMON; CETSOL	The goal for most industrial castings is to achieve a fine-grained equiaxed structure with minimal porosity and chemical heterogeneity. Equiaxed solidification is yet most affected by flow in the liquid phase. Grains can be entrained by the flow, modifying the flow itself, and can sediment or float due to density differences between the solid and liquid phases. In turn, solute species are redistributed and can show macrosegregation. For instance, the "sedimentation cone" in large cylindrical steel ingots is made of equiaxed globular grains accumulated by sedimentation at the central bottom part of the casting, exhibiting a large deviation from the nominal alloy composition. The reasons for globular grains are linked to a series of parameters including grain density (through interaction of the diffusion fields in the melt for heat and solute species generated by interacting grains) and convection that modifies the diffusion layers and the interface undercooling. Upon equiaxed dendritic growth, the selected crystallographic orientation for dendrite trunks and arms can also be modified, for instance changing from <100> to <110> directions. Experiments in purely diffusive conditions and with controlled convection are essential to quantify these effects. *Purely diffusive conditions. Controlled fluid-flow by magnetic field stirring; in-situ observation; long duration ISS experiments. Settling of equiaxed dendrites; thermal/solutal interactions; macrosegregation*

B3-EQ2. How does competition between grains proceed to create the columnar-to-equiaxed transition?	Growth under diffusive and well-defined fluid flow conditions	Nucleation kinetics; Growth kinetics; Modelling of microstructure evolution; Solutal interaction between grains	CETSOL; XRMON	The transition from constrained to unconstrained dendritic growth is at the origin of the columnar-to-equiaxed transition (CET). It leads to an evolution of the shape of the grain structure from (columnar) elongated to (equiaxed) more isotropic. This can be found in virtually all industrial processes based on melt solidification. However, depending on the final application, mainly fully equiaxed or fully columnar grain structures are required. On ground, the transition is achieved by controlling the conditions for directional solidification and/or achieving the conditions for formation of new grains, using grain refiners and/or favouring the fragmentation of a pre-existing dendritic microstructure. In the latter case, fragments are transported by floatation or due to liquid convection. Experiments in microgravity offer the possibility to study CET formation by varying furnace parameters, inoculation of the melt, alloy composition, thus eliminating fragmentation as a source of equiaxed grains. Not only the CET but also the intermediate regime of mixed columnar and equiaxed grains are considered for comparison with direct numerical simulation. *Absence of convection with reduced sedimentation; adjustable convection. In-situ observation; extended duration of ISS experiments.*

B3-EQ3 How do centrifugal forces impact on transition from columnar to equiaxed solidification?	Growth under different gravity levels spanning from µg to hyper-g-conditions	Nucleation and growth kinetics; Fluid flow and rigid body motion driven by acceleration forces	GRADECET	In some industrial applications centrifugal casting is used to produce near-net shape components, e.g. tubes for petro-chemical applications, turbine blades for aero-engine applications and last but not least medical implants. Microstructure evolution during solidification then depends on the acceleration forces (centrifugal and Coriolis) that may reach 20 to 30g (hyper-g). They lead to fluid flow whenever density inversion occurs in the liquid, but also to rigid body motion because solid grains (dendrites) are forced to move through the liquid in response to acceleration forces and viscous drag forces. Both flow and particle motion have a marked influence on the columnar-to-equiaxed transition, which can be investigated systematically in ESA's Large Diameter Centrifuge (LDC). Reference experiments in microgravity conditions offer the possibility to study the same transition in purely diffusive transport conditions and in the absence of particle motion, giving a baseline for computational modelling and simulation. *Directional transient solidification in µg, 1g and hyper-g conditions*
B4-DG1. How do interface stability and pattern selection depend on melt convection during directional solidification of a single solid phase?	Growth under diffusive and well-defined fluid flow conditions	Growth kinetics; Interface stability; Pattern selection; Modelling of microstructure evolution	MICAST; CETSOL; XRMON	Convection in casting not only modifies the kinetics of interfaces but also the selected growth morphology and pattern selection. The interplay between an advancing solidification front and fluid flow in the molten alloy still remains to be understood and carefully quantified. *Adjustable convection from purely diffusive to controlled convective flow. Long duration of ISS experiments.*

B4-DG2. What are the interactions between ceramic particles and an advancing dendritic front?	In-situ observation of growth front by high-speed video imaging; sample return for microstructure analysis	Particle pushing-engulfment-transition with dendritic solidification front	METCOMP (PF 2003-2008, TEXUS 49, MSL-EML)	Solidification of a dendritic microstructure from a liquid melt containing dispersed solid ceramic particles is a processing route to elaborate a composite material. How a homogeneous distribution of the ceramic particles in the metallic matrix can be achieved is a main technological question. The interaction of ceramic particles with an advancing dendritic solidification front is a very complex process in the presence of convection and gravitation. Growth dynamics and morphology of the solid-liquid interface, and also transport phenomena in the liquid ahead of the interface due to convection and sedimentation, influence embedding or pushing of particles. Microgravity experiments in the EML give the opportunity to study the interaction of the dendritic interface with ceramic particles by changing growth velocity of the dendrites and convection level in the melt. *Investigation of undercooled metallic model systems with ceramic particles in the EML; low convection; in-situ observation of solidification front, freezing of microstructure; after return of the samples, analysis of dendrite/particle pattern.*

B4-PG1. How do bands and island patterns form?	Solidification of peritectic alloys at extremely low speed and high thermal gradient under low convection; in-situ observation of transparent alloys	Pattern formation in peritectic alloys	METCOMP (MSL-SQF, TRANSPARENT ALLOYS furnace)	Peritectic alloys, in which the primary α phase formed in the liquid transforms into the peritectic β phase below the invariant temperature, have been shown to behave almost as eutectic alloys at very low speed. Indeed, under conditions where both phases should grow as a planar front, neither are stable. As a result, alloys with a hypoperitectic composition can either form alternated bands or grow in a cooperative way with a front of α and β lamellae. While a much better understanding of such microstructures has been gained over the past two decades thanks to ground experiments, buoyancy and convection strongly influence their formation. Directional solidification experiments of peritectic Cu-Sn alloys are planned in the MSL-SQF under microgravity conditions in order to minimize buoyancy and convection. In a parallel approach transparent peritectic model alloys will be investigated in the TRANSPARENT ALLOYS (TA) furnace on the ISS. These systems are of scientific interest as they allow the observation of growth mechanisms directly by optical methods. *Variation of thermal gradient and growth velocity; low convection; in-situ observation (TA); extended duration of ISS experiments; microstructure analysis on ground.*
B4-EG1. What are the explanations for the formation of low symmetry patterns (lamella-to-rod transition) and coexistence of distinct patterns?	Growth under purely diffusive conditions	Pattern evolution	SETA; SEBA	Eutectics have emerged as novel materials with very promising structural properties. Solidification of eutectic alloys results in regular arrangements of finely dispersed distinct crystal phases in lamellar, fibrous or more complex patterns evolving during coupled growth at the solid-liquid interface. The prediction and control of these self-organizing polyphase patterns stimulates abundant laboratory research linking fundamental and applied sciences. Research efforts are still required to fully understand pattern formation and learn how to prevent pattern defects, specifically in bulk samples, calling for dedicated microgravity experiments with metallic and organic eutectic alloys. *Directional solidification with adjustable thermal and compositional gradients and growth rates*

B4-EG2. What is the dynamic for two- and three-phase growth patterns in ternary or multicomponent alloys?	Growth under purely diffusive conditions	Pattern evolution	SETA SEBA	While investigations of eutectic microstructure in binary alloys are common, ternary or multicomponent are rarely studied. The dynamics of two- and three-phase growth patterns also requires the absence of convection. The reason for this is that, in general, the segregation of one of the two chemical species in off-eutectic alloys, or that of a third component in ternary alloys, creates constitutional density gradients in the liquid, driving convective motion in the gravity field. *Directional solidification with adjustable thermal and compositional gradients and growth rates*
B5-S1. What is the role of shrinkage on the redistribution of species?	Sample deformation; Redistribution of species	Shrinkage-induced segregation; Modelling of segregation	CCEMLCC	Solidification shrinkage due to the liquid-to-solid density change induces liquid flow that influences the formation of microstructure and segregation. This flow is naturally present in microgravity. As a result, inverse segregation close to the skin of the products formed in contact with a mould is typical of shrinkage flow. Characterizing the effect of shrinkage flow in the absence of buoyancy-driven convection is required to check prediction of segregation solely due to shrinkage. *Triggered growth of EML samples using a chill plate.*
B5-SP1. What are the parameters that dictate the final fraction of microstructures and phases upon solidification of a melt?	Phase fraction from levitated samples with no buoyant natural convection; Distribution of microstructures and phases in directionally solidified samples with no buoyant natural convection	Solidification path; Nucleation / growth sequences	NEQUISOL; CETSOL; CCEMLCC	While the selection of phases and microstructural patterns can be studied in microgravity, the solidification path is also of interest. It mainly consists of the final distributions of phases and its chemical compositions, as well as its sequence of precipitation from the melt. This is expected to provide the main parameters explaining the distribution of phases, considering the role of nucleation undercooling of each new microstructure formed from the melt, its growth kinetics, the role of diffusion of chemical species in the various phases, etc. The microgravity samples are provided with ideal non-equilibrium solidification conditions as little macrosegregation is observed that can only be linked to the development of the microstructures in the absence of thermosolutal convection. This provides benchmark data for modelling of microsegregation. *Purely diffusive conditions. Long duration of ISS experiments.*

B5-T1. What is the role of thermo-mechanical deformation of the solid phase on the redistribution of species and the creation of defects in the mushy zone?	Sample deformation; Redistribution of species	Deformation-induced segregation	CCEMLCC	Thermomechanical deformation of a solid dendritic phase induces liquid flow in the existing mushy zone. Stresses and deformations can accumulate in the solid phases upon cooling and reach the conditions for hot tearing, a defect manifesting itself by a crack formed in the solidification interval. The deformation-induced flow can also redistribute interdendritic solute species, thus creating macrosegregation, the main reason for central line segregation in continuous casting of steels. Links between these phenomena and the interdendritic microstructure are observed, but still hardly explained considering the sophisticated interplays between thermodynamic, liquid flow, segregation and thermomechanical deformations. The absence of buoyancy-driven flow in microgravity is expected to provide a framework for quantitative study of deformation-induced flow and defects. *Triggered growth of EML samples using a chill plate.*

The above tables should not be seen as an exhaustive list of scientific objectives. Instead, it represents a “snapshot” of the main fundamental scientific questions that scientists face at the time of the preparation of the present issue of this document. Some questions might be answered in the near future, while new questions might arise.

4.4. Applications

Direct measurement of thermophysical properties of metallic melts and progress in understanding structural evolution upon cooling will provide the fundamental information needed to accelerate the rate of innovation in manufacturing and materials engineering through computer simulations by:

- predicting microstructure and defects in castings,
- controlling microstructure for designed mechanical and physical properties,
- creating new alloys and solidification paths for novel structures and properties,
- generating new industrial application for solidification processed materials.

Among potential applications are:

- casting processes (Fe-, Ni-, Ti-, Al-, Mg-, Cu alloys, refractories, metal-matrix composites),
- crystal growth of poly- and single-crystalline materials (turbine blades, semiconductors),
- metallic glass production/wires/fibres,
- crystal – glass composites,
- additive manufacturing - 3D printing,
- spray forming and powder production,
- surface modification by spraying techniques.

Transfer of results towards innovation in manufacturing and materials engineering will be ensured by the actual and future industrial partners of microgravity-related projects, as well as by software companies specialized in modelling of metal casting technologies.

4.5. Industry Partners to On-going Materials Science Projects in Microgravity Related to this Roadmap

ALCOA-KOFEM (HU)
APERAM ALLOYS IMPHY (FR)
ARCELORMITTAL (FR)
AREVA NP (FR)
ASCO INDUSTRIES (FR)
CSM (IT)
DEUTSCHES KUPFERINSTITUT (DE)
EQUISPHERES (CA)
EVRAZ (CA)
HYDRO ALUMINIUM (DE)
INCAAL NORVENICH (DE)
INDUSTEEL (FR)
INGENIEURBÜRO SELLGER (DE)
INNOVAL TECHNOLOGY (UK)
INOTAL (HU)
KME GERMANY (DE)
NEMAK (HU)
NETZSCH (DE)
PX SERVICES (CH)
RGS DEVELOPMENT (NL)
SCHWERMETALL HALBZEUGWERK (DE)
SNECMA (FR)
TATA STEEL (UK)
THERMO-CALC SOFTWARE AB (SE)
TRANSVALOR (FR)
VDM METALS (DE)
WIELAND-WERKE (DE)
ZOLLERN (DE)

ROADMAP 5: ASTROBIOLOGY - ROADMAP FOR A NEAR FUTURE

5.1. Introduction

Astrobiology is an interdisciplinary scientific field focused not only on the search for extraterrestrial life, but also on deciphering the key environmental parameters that have enabled the emergence of life on Earth on a foundation of molecular evolution. Understanding the physical and chemical parameters for this emergence is fundamental not only for discovering life or signs of life on other planets, but also for understanding our own early terrestrial environment, which enabled it. The field of astrobiology thus encourages combining different perspectives, such as the conditions in which life appeared on the primitive Earth, the physicochemical limits of life, exploration of habitable environments in the Solar System, and the search for signatures of life beyond Earth. The interdisciplinary field of astrobiology therefore encompasses many scientific communities comprising physicists, astrophysicists, chemists, biologists, planetologists, geologists and many others.

Today, it is impossible to say conclusively that terrestrial life is unique, or that there is an almost infinite number of inhabited worlds hosting multiple life forms throughout the universe. "Are we alone in the Universe?" is certainly one of the most exciting science questions occupying public attention. Indeed, astrobiology research has entered a promising and challenging phase since the late nineties as new tools, new discoveries, and new concepts have profoundly changed the face of the discipline.

Recent discoveries are opening new perspectives in the field: new understanding of planetary system formation including the specificity of the Earth among the diversity of planets, new insights on the origin of water on Earth and its unique combined properties that make it an ideal solvent for the emergence of carbon-based life, the new idea that the Earth could have been habitable during the Hadean Era, new understanding of the inventories and sources of endogenous and exogenous organic matter, and new concepts about how chemistry could evolve towards "biological" molecules and systems. In addition, many new findings show the remarkable potential life has for adaptation and survival in extreme environments. Concerns have emerged that our own exploration could disseminate terrestrial life on the worlds we are exploring, jeopardizing our original search for endemic life on those worlds. All these results from different fields of science are guiding our perspectives and strategies to look for life in other Solar System objects and beyond. What are the signatures of life for which we could be looking; where and how should we look? are anything but trivial questions. These are questions that will probably be highly debated in coming decades.

The consensus in the astrobiological community is that the origins of life (and most probably its sustainability) require liquid water, most of which was likely imported from space after the Earth formed, and organic matter, either from endogenous sources (atmospheric and/or geochemical synthesis) and/or exogenous sources (e.g. comets, carbonaceous asteroids and micrometeorites). While one group of scientists struggles to understand the origins of life, another has revealed the astounding ability of living systems to adapt to the most extreme and improbable environments on Earth. It seems that almost all terrestrial environments, hot or cold, dry or wet, neutral, basic, or acidic are inhabited. Although it remains unclear whether life has the capability to emerge in such extreme conditions, its tremendous capacity to at least adapt to different conditions provides perspective for the search for life elsewhere in the Solar System. Whether on Mars, or in the oceans of the satellites of the outer planets (such as Europa, Ganymede, Callisto, Titan or Enceladus), the Solar System may harbour niches that are favourable for the emergence of life.

Since 2011, ESA has funded a topical team on astrobiology. The team was asked to produce an update covering the recent profound achievements and transformations in the field of astrobiology that have occurred in recent years and to focus specifically on experimental studies either in the field (i.e. using Earth as a tool for astrobiology) or in space, (i.e. using space as a tool for astrobiology). This document presents a roadmap for astrobiology in the near future as an outcome of the work of the Topical Team. Most of the community involved in the discussion of this roadmap was also involved in the European Astromap Roadmap, developed through the FP7 AstRoMap project.

5.2. Relevance to Human Space Exploration Goals and Societal Issues

5.2.1. Support of Human Space Exploration

- Development of innovative hardware needs to be continued for experimentation on the International Space Station and beyond (adapted from, and for, nanosats and other small payloads as well as custom-designed for the ISS)
- ESA provided international leadership in experimentation related to astrobiology conducted in space in the 1990's and 2000's. Since the early 2010's, USA, Japan and Russia are taking over much of the European experimental leadership to conduct their own experiments (O/OREOS, Tanpopo (EXPOSE-like experiment), BION (Biopan & STONE-like experiments)). The next decade will be critical if ESA is to regain clear leadership of this field. The science community is well structured (Topical Team, Roadmaps, EANA), and experienced in the field as a formal science along with its space-related activities.

5.2.2. Relevance to Societal or Terrestrial Issues

- Astrobiology is of huge public interest (viz. media coverage for Rosetta, Curiosity, water detection on Mars, and their impacts in the media are major and worldwide).
- Astrobiology plays an important role in education in science at all levels. How to address the question of the origins of life and how to search for life from a scientific and technical perspective are very effective means to gain the attention of students and to direct them to broader science subjects, emphasizing the crucial role of interdisciplinary approaches.
- Innovation for future, space-qualified instrumentation for future facilities will impact industry and future Solar System exploration programmes. For instance, instruments that can be used for "life detection" after their improvement for use in space (e.g. on specific space platforms) will be very robust and can also be applied in terrestrial extreme environments. The benefit of these instruments, which can additionally be used on Earth, leads to a better understanding of e.g. the micro-environment and the interactions within biomes with less manipulation of the environment by the instruments.

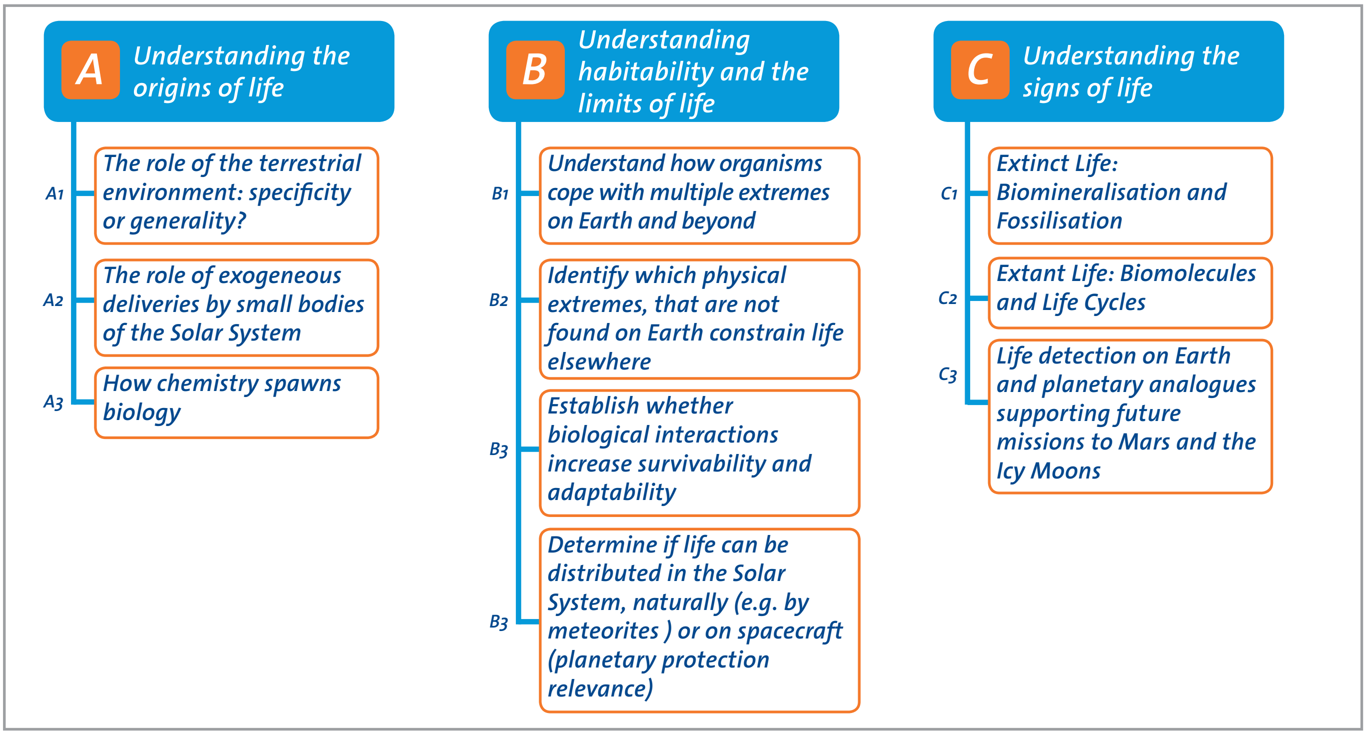

Figure 5.1. Specific objectives in astrobiology.

5.3. Specific Objectives / Questions to be Addressed Up To 2024

The astrobiology science community involved in ESA activities has defined and agreed on the following top science objectives and related sub-objectives (Fig. 5.1). The interdisciplinary nature of the entire field prevents any prioritization among them; they are closely interwoven.

5.3.1. Question A - Understanding the origins of life

Life on Earth is our only comprehensive reference and constitutes a scientific context for astrobiology studies. How life originated on Earth is a central question to guide our search for life beyond our planet.

Objective A.1: The role of the terrestrial environment: specificity or generality?

While the terrestrial environment, with stable liquid water at the surface, is unique in the Solar System today, this was not always the case. When life emerged on the Earth more than 4 billion years ago, other planets (Mars and perhaps Venus) also exhibited this property. But such a planet has yet to be found in the large inventory and expanding number of exoplanets. It is crucial to understand the role of the composition of the primitive atmosphere and the composition of the lithosphere (e.g. organic synthesis in hydrothermal vents), as well as the role of radiation provided by the Sun. These are all critical factors to be addressed.

Objective A.2: The role of exogenous deliveries by small bodies of the Solar System

It is now established that organic material has been provided to Earth's environment via meteorites and micrometeorites originating from carbonaceous asteroids and comets. Such material was delivered to the early Earth after a long journey in space. It is important to understand how much of this material has been delivered to Earth, how space radiation and the mineral matrix of the small bodies may affect the inventory (nature, amount and distribution), and its significance in the prebiotic chemistry leading to the origins of life.

Objective A.3: How chemistry spawns biology

Life could be defined as any auto-replicative system that evolves by natural selection. The key point for the study of the origins of life, from which all other questions derive, is to understand how Nature makes the transition from inert to living (molecular) systems (a process called abiogenesis). Organic chemistry is clearly central to this integrated method, and recent improvements have been achieved in this field in the past few years.

5.3.2. Question B - Understanding habitability and the limits of life

The study of life on Earth has shown the astounding ability of living systems to adapt to the most extreme and improbable environments on Earth (with regard to temperature, pressure, pH, humidity, salinity, radiation dose, etc.). It seems that almost all terrestrial environments are inhabited. Although it remains unclear whether life has the capability to emerge in extreme conditions, its tremendous capacity to at least adapt to such conditions provides perspective for the search for life elsewhere in the Solar System and broadens the scope of what "habitable" can mean.

Objective B.1: Understand how organisms cope with multiple extremes on Earth and beyond

Most of the environments considered as extreme that are inhabited by organisms on Earth combine several parameters that are considered "extreme" in themselves. Studies of the effects of individual and combined "extreme" environments can be performed by the exploration of Earth analogue sites, by the use of simulated environmental parameters in the laboratory, and by space experiments. These studies are needed to support exploration strategies beyond our planet. How resistance to one extreme environmental parameter increases (or decreases) the resistance of a given organism to a different harmful stress factor not naturally occurring in its environment is widely discussed in the science community.

Objective B.2: Identify which physical extremes that are not found on Earth constrain life elsewhere

While several physically extreme environments are naturally present on Earth and inhabited, some extraterrestrial conditions are specific to space and/or planetary or planetary satellite environments. Low pressure down to space vacuum, exceptionally low relative humidity, and in particular highly ionizing and short-wavelength solar UV radiation are quite common in space and on the surfaces of solar system bodies, but are not present on Earth, and can only partly be simulated due to their complexity. Access to space environments in order to expose organisms on platforms that enable in-situ measurements of metabolic, genetic, and/or phenotypic changes, as well as proliferation, is therefore important to tackle these research topics.

Objective B.3: Establish whether biological interactions increase survivability and adaptability

While one specific organism may not be able to cope with extreme parameters, it could be able to survive and adapt to drastic environmental changes (such as the ones that occurred on Mars) in association with others of its own kind (biofilms) or other kinds (ecologies).

Objective B.4: Determine if life can be distributed in the Solar System naturally (e.g. by meteorites) or on spacecraft (planetary protection relevance)

An increasing number of organisms that are adapted to extreme environments are being discovered, in particular when survival is the criterion rather than adaptation. The possibility that organisms could travel and survive on meteorites ejected from Mars to Earth should be investigated, in particular with a view towards Planetary Protection issues. We must assume that space exploration could mean contamination. In-space in-situ experiments are needed to better understand survival strategies of organisms and their means of adaptation to new environmental parameters not found on Earth. Increased knowledge of these survival strategies of organisms and their limits will consequently lead to the development of improved means for decontamination procedures. Currently, reliable decontamination procedures are the only way to make spacecraft as clean as possible, and to thereby minimize contamination of other worlds with terrestrial life. This is true in particular for destinations that are considered habitable and may have developed their own life forms.

5.3.3. Question C - Understanding the signs of life

"Understanding the signs of life" in the Solar System focuses on "cells", their remnants, and clearly cell-related biochemistry, as well as life-driven transformation of its environment. The main objectives of this topic focus on detecting signs of life using instrumentation and imply understanding the composition of a cell and the stability of the biomolecules that form it.

Objective C.1: Extinct Life: Biomineralisation and Fossilisation

Promising methods to search for life and in particular for past life on Mars would search for traces of life (organic, geochemical, isotopic or morphological) near the surface or even at the surface. The interaction of these traces with UV radiation, and in the presence of different atmospheres, temperatures, and humidities needs to be investigated, using references such as "terrestrial fossils" from Earth. This can be done in simulated conditions on the ground and, even better, in space.

Objective C.2: Extant Life: Biomolecules and Life Cycles

It is important to analyse biomolecules such as the membranes, lipids, pigments, proteins, DNA, RNA, and ATP from which cells are made. The life cycle of cells potentially influences their environment and will help classify and identify extant life in any environment on Earth or in space. Characterization of life cycles must also be possible because the amount or presence of some molecules within a cell changes over time.

Objective C.3: Life detection on Earth and planetary analogues supporting future missions to Mars and the Icy Moons

A systematic approach for detection of microbial life forms on Earth and in space can be based upon the collection of data from the known microbial world. Studies are needed to determine the signs of life using various detection instruments under various environmental conditions on planetary-analogue field sites and in planetary simulation experiments, as well as in space. Each of these parameters could alter the detected biosignatures and might hide one of them. This should be systematically recorded and included in databases.

5.4. How Available Platform Opportunities and Programmes (Both Flight & Ground) can be used to Address Roadmap Objectives

- The above subjects are addressed by the astrobiology experiments selected during the ILSRA 2014 AO (EXPOSE continuation, and a Cubesat-like payload system). Experiments of high scientific merit are regarded as a priority by the science community and should be implemented. Experiments addressing the category "understanding the origins of life" are, however, underrepresented in the current ESA project pool. The following discussion and recommendations are mainly the outcome of the ESA Astrobiology Topical Team (2011-2014) as presented in Cottin et al. (submitted) .
- The science community recommends the resumption of Biopan-like experiments. While Russia is implementing similar experiments, ESA has focused only on ISS EXPOSE and similar experiments. Although valuable, the timing of preparation for experiments on the ISS is extremely long: a few months between sample delivery and actual launch, sometimes a few weeks inside the ISS before EVA, 18 to 24 months in space, and then a few weeks to return samples to terrestrial laboratories for analysis. Biopan samples, on the other hand, are prepared just 2 to 3 weeks before launch, and analyzed in laboratories a few days after returning to Earth. Some samples are not suitable for study on the ISS due to their poor stability over such long storage and exposure durations. They should be exposed for short durations (a few weeks) in order to determine whether they should occupy a valuable position in an exposure facility for more than a year in space. In addition, continuation of long-term exposure facilities is well suited to the study of highly UV-resistant molecules or microorganisms and the long-term evolution of microbial colonies (generally in the absence of solar UV). The orbits or surfaces of the Moon, Mars, or Mars' satellites, as well as space mission hitchhikers, could provide environmentally unique, privileged locations for such studies in the future.
- STONE-like experiments should resume. They have no equivalent since 2007, despite the fact that science related to the stability of minerals and organic compounds during meteoritic infall has important astrobiological significance. A study of how best to resume this class of experiment, whether on a Foton capsule or as impact modules ejected from the ISS, should be conducted. It must be noted that Russia is now conducting experiments directly inspired by this original idea developed by the science community of ESA member states.
- The development of individual retrievable satellites returning their payloads, or in their entirety, to the ground is needed for all experiments that benefit from post-flight on-ground laboratory analysis of samples in addition to in-situ measurements.
- Facilities far from the polluted environment of the ISS should be made available. Gas plumes from Soyuz and ISS resupply vehicles, as well as degradation and outgassing of external ISS materials, along with oxygen radicals from Earth's residual atmosphere below 500 km, make protection of samples by optical components such as MgF_2 windows necessary, thus blocking VUV photons below 115 nm. The flux at these short wavelengths, although low, is required for photodissociation of very relevant molecules such as N_2 (< 100 nm). Direct exposure of samples to full-spectrum solar radiation should be possible without protective windows to block chemical pollution.
- Environments with significant fluxes of energetic charged particles (GCRs, SPEs) should be accessible. The ISS altitude is well within Earth's magnetosphere, which blocks many of the most damaging particle types and linear-energy-transfer ranges. An exposure environment combining high fluxes of both photons and energetic charged particles would be a major improvement compared to existing facilities in space as well as in Earth laboratories. Polar, transfer, geostationary, cis-lunar, or other beyond-LEO orbits will be necessary for future facilities.
- Sample analysis should be feasible throughout the exposure period, not only before launch and after return to Earth: in-situ analytical instruments are required. OREOcube will be equipped with a UV-vis-NIR spectrometer that provides useful information about the electronic structure of thin films, particularly those with informative bands in the visible and near-UV regions (organometallics as well as many metal oxides and most PAHs, for example). For most astrochemistry experiments, optimal molecular characterization, including structural changes and new product formation, also requires measurement of the details of molecular bonding. This can be provided by an IR or Raman spectrometer that covers the 4000 – 1000 cm^{-1} energy range; such an instrument would make the return of samples to Earth less of a necessity. This capability for vibrational spectroscopy is well within the technical reach of nanosatellites, including those destined for polar or geotransfer orbits. In addition, other techniques for characterization may be required according to the details of the samples and their expected response to the space environment: laser-induced fluorescence and mass spectroscopic analysis (of headspace gases above samples) are

two examples. In a more general perspective, fluorescence-, IR-, LIBS-, mass-, Raman-, UV-VIS-spectroscopy etc., are acknowledged as important techniques for sample characterization in space during ongoing experiments.

- Temperature control is an additional priority. Currently, solid films and gaseous mixtures are exposed at temperatures that are largely uncontrolled during exposure. Large temperature fluctuations have been observed on the Biopan, EXPOSE, and O/OREOS experiments (-20 °C to +45 °C). This wide temperature range prevents the study of compounds having significant vapor pressure above 0 °C. Thermal control can therefore broaden the range of compounds that can be studied in exposure facilities. Moreover, with regard to organic astrochemistry, radiation-driven changes occur in the gaseous and solid phases as well as, for a large fraction, in the ice phase at low temperature (< 100 K) at the surfaces of the icy moons of the giant planets, in comets, and in interstellar dark clouds. Future exposure facilities should include cold sample locations where icy mixtures can be prepared, after launch, from gaseous mixtures (H_2O, CO_2, NH_3 and CH_3OH for instance). Also, for the exposure of organisms to environments similar to Mars or Europa, for example, with respect to temperature, cold exposure platforms for long term exposure (> 2 weeks) are needed.
- A promising method to search for life and in particular for past life on Mars would be to search for traces of life in the form of biosignatures that may be present in rocks close to or even on the surface. However, lack of full understanding of the effects of interacting UV radiation with biosignatures (especially organic) over long geological time scales and in different atmospheres and temperatures compared to environmental conditions on Earth make it important to study terrestrial reference systems, i.e. "fossils from Earth", under simulated conditions on ground and, even better, in space.
- Living organisms should be exposed to the space environment in the metabolically active and, for many, reproductively active forms. It is already known that, in actively metabolizing organisms, non-terrestrial gravity levels including microgravity can have significant effects, whether directly or due to modification of mass-transport mechanisms. Similar significance also applies to exposure to radiation, the other space environmental parameter that most perturbs living biological systems removed from their terrestrial habitats. To understand the cellular and molecular mechanisms of adaptation and evolution, for example under Mars or space conditions, investigations require active metabolism, at least temporarily, and in some cases for multiple generations.
- Long-term experiments with actively growing organisms offer a new horizon for biology exposure experiments. Adaptation and optimization of existing, well-developed laboratory technologies are necessary for space application, including monitoring and control of temperature, relative humidity, pressure, pH, gas-phase composition, the supply of nutrients, the removal of waste products, and the delivery of reagents. Small space bioreactors and microevolution chambers are currently in the infancy of conception and development; they should include options for automatic sub-/sampling at regular, predefined but variable intervals, options to adjust or redirect the experiments from the ground by telemonitoring and telecommand, as well as appropriate in-situ / in-orbit observation and analysis to detect metabolic changes and quantify adaptation processes.
- A major hurdle for performing experiments beyond Earth is the effort and cost required to launch suitable hardware into space. With ongoing efforts at miniaturization in practically every industrial and scientific sector, small-scale and light-weight space hardware is becoming increasingly available with expanded technical and analytical capabilities. This trend also affects the design and development of small satellites and nanosatellites. The "Cubesat" format (one or multiple conjoined cubes of 10 cm length) is by now an internationally accepted platform for small satellites and offers increasingly sophisticated analytical measurement capabilities in small, lightweight, low-power, inexpensive packages adaptable to many spaceflight and planetary applications. The rapid advances in miniature, micro, and integrated technologies support the development of innovative small payload systems that can be accommodated on small satellites, returning exciting science results at a fraction of the cost of large missions. The use of nanosatellites for future astrobiology experiments would perfectly address the increasing number and flexibility of experiments requested by the community.
- Miniaturized instruments and microanalytical systems are driving the capability of small-satellite science missions forward by harnessing recent advances in microfluidics, microelectromechanical systems (MEMS) including sensors and actuators, polymer microfabrication technologies, low-power microelectronics, miniature high-efficiency motors, advanced materials, and integrated/fibre optics including micro/miniature light sources, cameras, and spectrometers. Cubesat payload technology further provides an outstanding opportunity to enable innovative technological advances in sensor and miniaturized instrument design for astrobiology applications in terrestrial field research and space environments inside (or on the outside of) the ISS, planetary orbiters and landers, and lunar platforms.

ROADMAP 6: UNDERSTANDING THE IMPACT OF GRAVITY ON BIOLOGICAL PROCESSES, CELLS AND ORGANISMS

6.1. Introduction

It has been clearly demonstrated that biological systems (plants, animals or cell/tissue models) exhibit altered function and behaviour in different gravity conditions. While the response of different cell types has been described in some detail in human, animal and plant models, the intracellular regulatory pathways and their dynamic adaptation and cross-talk remain poorly understood. Studies on whole organisms (in vivo) and cells or tissues (in vitro/ex vivo) are not only complementary but also mutually corroborating. In these models, several molecular pathways involved in epigenetic mechanisms, genetic expression/ regulation/repair, immune system dysfunction, ageing processes, tissue remodelling, and stem cell proliferation and differentiation have been characterized. This makes altered-gravity research on such models extremely efficient and promising. However, it has to be stated that tissue and whole organism research is especially hampered by the strict limitations of technological and instrument capabilities available for space missions.
Plant biology experiments carried out in space using molecular, cellular and physiological approaches have also shown that key parameters appear altered in the microgravity environment. In many cases, the alterations found at the cellular and molecular level were homologous to those reported for animal cell types or unicellular systems, although some processes, such as gravitropism, are specific for plants. Recent studies have reported plants to be capable of development in the space environment, although adult plants often show some abnormalities. The underlying mechanisms that enable plants to counteract the gravitational stimulus and develop and survive in the space environment need to be further identified. The relevance of the related questions are further emphasised by the notion that photosynthetic organisms will be a central building block for biological life support systems essential for deep-space exploration missions.

It is the general consensus of the scientific community working on space-related research that in the following years, up to 2024, the implementation of research models that more closely resemble biological systems needs to be encouraged alongside the older and reliable traditional systems. Adequate technological support measures must be developed and applied in order to ensure a more efficient evaluation of the status of space experiments. In order to maximise the use of resources and time, a better integration with hardware that is currently available for the ISS in the JAXA and NASA modules should be strongly encouraged.

This roadmap provides a summary of the key objectives and questions that need to be addressed with regard to the responses that organisms exhibit under altered gravity conditions, and the relevance of these aspects on the future of space exploration. It is now time to take the best advantage of existing knowledge and available technological expertise to advance our understanding of how biological systems react and adapt to altered gravity.

6.1.1. Identify where there are Links or Input from other Roadmaps or Assessments

The aims and considerations of this roadmap are closely connected with the issues addressed in Roadmaps 5, 7 and 8 with some overlapping aspects, including the identification of countermeasures to prevent or cure deleterious adaptive responses. Moreover, this roadmap addresses the key recommendations listed in Section 6.2 (Life Sciences) of the ESF Independent Evaluation of ESA's Programme for Life and Physical Sciences in Space (ELIPS) Report (2012)
http://www.esf.org/fileadmin/Public_documents/Publications/elips_01.pdf :

- Promoting cutting edge science and cross-disciplinary interactions in life sciences
- Integrated physiology
- Exercise, muscle/bone
- Neuro-vestibular
- Immunology

- Nutrition and metabolism
- Cell and molecular biology
- Developmental biology
- Biological effects of radiation
- Plant Biology
- Gravitactic and phototactic responses in microorganisms
- Microbiology

This roadmap also complies with recommendation number 4 on the use of Ground-based Facilities (GBF), from Section 2.1 (ELIPS in the Broader Scientific Landscape) of ELIPS Report 2012 and addresses the target topics of the ILSRA calls and the Horizon 2020 objectives.

6.2. Relevance to Human Space Exploration Goals and Societal Issues.

Biological research under space conditions provides the fundamental basis for human space exploration. Space-related biological research has clearly demonstrated its valuable contribution to the advancement of science in its own right over the last decades. In this context, research activities planned up to 2024 will result in:

- a better understanding of the gravity-related responses and adaptation processes of the human body while in space, such as genetic aberration, DNA repair, stress response, tissue degradation, metabolic changes, etc;
- characterization of the mechanical sensitivity and morphology of cell models and organisms to provide baseline knowledge to work on in view of long-duration manned space missions.
- identification of protective measures for long-term human space missions (such as orbital flights, ISS, Mars and Moon base missions);
- a better understanding of both plant and animal life cycles in altered gravity conditions in order to identify critical points of susceptibility to gravity, improving the definition of requirements in the design of bioregenerative life support systems;
- identifying how gravity shapes organisms and ecosystems.

Relevance to societal and terrestrial issues of the research activities carried out within ESA's space research programme is also of paramount importance, and experimentation to be carried out up to 2024 is expected to contribute to the following aspects:

- a better understanding of the cellular mechanisms which translate mechanical signals into biochemical responses, leading to the development of new strategies for preserving/repairing mechano-sensitive human tissues that could find an application in general medicine, diagnostics, rehabilitation and physical training;
- identifying possible alterations in regenerative processes that can be very helpful to the development of regenerative medicine;
- development of effective technological platforms for generating human tissue/organ equivalents that would also be greatly valuable to terrestrial patients affected by communicable and chronic non-communicable diseases, as well as natural ageing, for which actual therapeutic strategies are either ineffective and/or pose a high social burden;
- development of new methodologies and technologies to be implemented in space research will further boost technologies currently used on earth, leading to a new generation of equipment used for life sciences and pharmaceutical industry applications;
- a better understanding of the interaction between environmental stresses, particularly when evolutionary novel gravitational stress is involved, may lead to improvements not only in space agronomy but also in sustainable agriculture on earth, particularly in the use of new species under unusual conditions on our planet.

6.3. Top Level Key Open Questions

As countless biological experiments conducted under true or simulated microgravity have demonstrated already, cells do react to weightlessness. The extent of their response, however, is variable in its appearance and relates to the type of cells under investigation. Thus, the focus of the research activities carried out up to 2024 should be on further detecting and characterizing the underlying cellular mechanisms that are causing the multifaceted responses of cells to the changed influence of gravity, using isolated cells and more complex cellular aggregates. It is of central importance to thoroughly identify and investigate the relevant cell structures.

Several animal model organisms are suitable for studies in altered gravity conditions. Recently, the focus has been put on organisms that are sufficiently complex (e.g. those with a central nervous system or vertebrates) to be interesting for human spaceflight and simultaneously simple enough to show rapid development, good regeneration capabilities, and be very easy to handle and maintain.

One of the most attractive challenges of space plant biology for the near future is to investigate the molecular processes networks, physiological mechanisms and structural modifications involved in counteracting the effects of altered gravity conditions. Aiming for a stable realization of plant life cycle completion, a major challenge is to identify the phases in which plants are more sensitive/vulnerable to altered gravity and to investigate the mechanisms by which gravity alters/prevents specific developmental processes.

6.4. Overview of Open Questions

6.4.1. Question A - How are Cell Structure and Function Influenced by the Influence of Gravity?

While the responses of various cell types to gravity have been described in some detail, the intracellular regulatory pathways involved and their dynamic adaptation and cross-talk remain poorly understood. This is largely due to the fact that previous experiments aimed at evaluating whether gravity alterations are able to modify cell phenotypes and were therefore designed to obtain end-point data. In most of these experiments, cells were also considered as “closed compartments”, without taking into account their interaction with their surroundings (extracellular matrix composition and stiffness, cell-cell interactions, etc.). Similarly, the study of interrelationships between different regulatory pathways or the eventual additional effect of radiation was not considered a priority, even though they are clearly closely connected. Gravity can lead to changes in cell proliferation, differentiation, function, signalling, gene expression, chromatin structure as well as overall and internal structural adaptations. In the past two decades, important steps have been made in the field of mechanobiology, and these advances should be used to evaluate the response of single cells to changes in the influence of gravity. Recent results indicate that microgravity imposes a stress (either osmotic or oxidative) on cells.

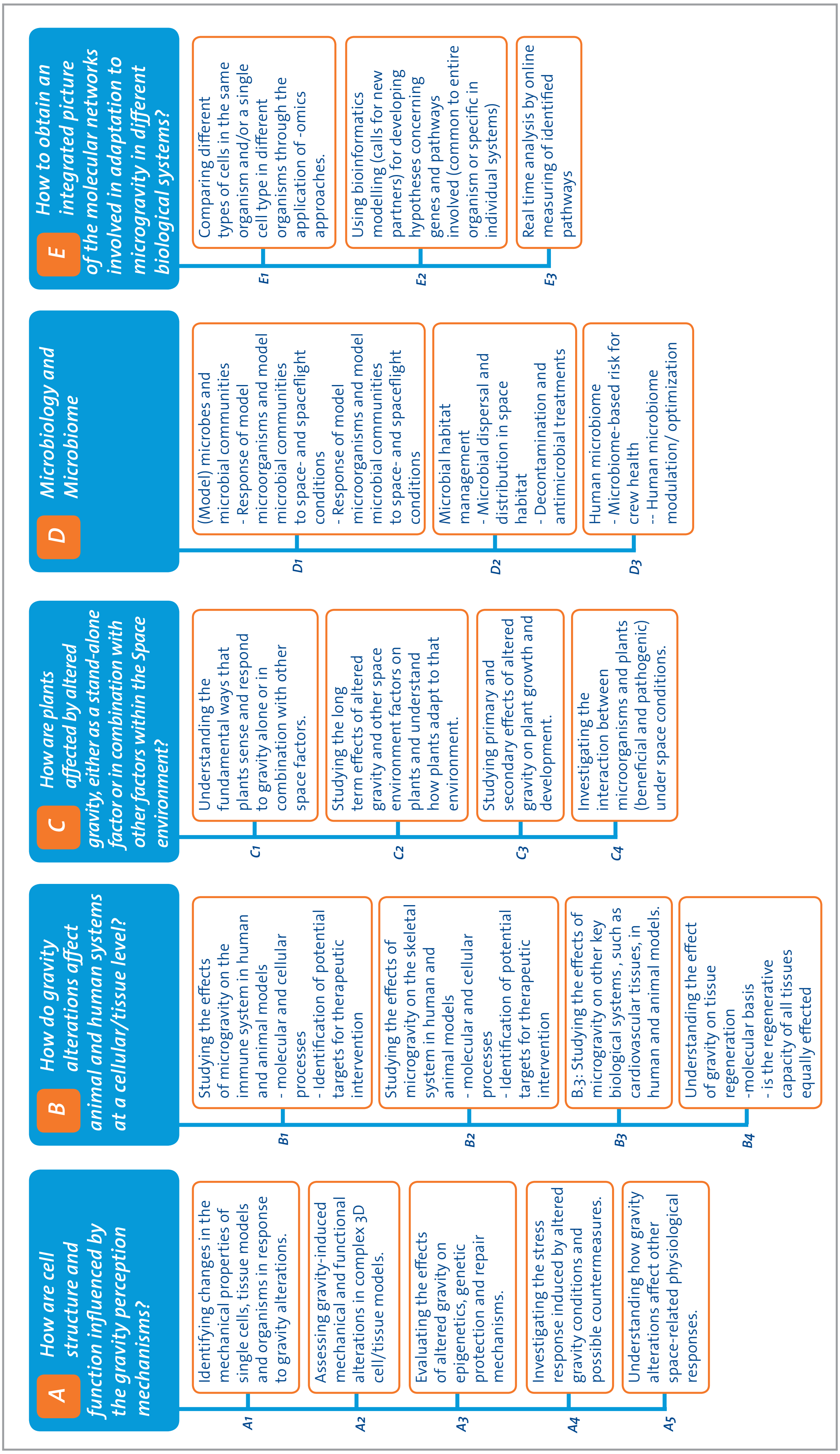

Figure 6.1: Open questions on understanding impact of gravity on biological processes, cells and organisms

Objective A.1: Identifying changes in the mechanical properties of single cells, tissue models and organisms in response to gravity alterations.

Microgravity provides a unique environment where cells no longer experience the mechanical stress of their own weight. Although this force is, on a cellular level quite small, research in microgravity will bring us basic understanding on the impact of mechanical forces onto cells such as:

- How are the mechanical properties of cells changed by altered gravity?
- How are cell-cell and cell-environment interactions modified by microgravity?
- What are the mechanisms and regulatory pathways underlying gravity-sensing in non-specialised cells?
- What are the interactions between gravity sensing pathways and other signalling cascades?
- How can we translate these mechano-sensing properties toward application for crew and general public health?

For example, previous studies have shown stiffness-dependent differentiation of stem cells, stiffness-directed cell motility (durotaxis) and the importance of the environmental mechanical properties for proper cell differentiation.

Objective A.2: Assessing gravity-induced mechanical and functional alterations in complex 3D cell/ tissue models.

Complex 3D cell/tissue models are a relatively novel and valuable approach to gravity-related space research. Such models mimic the physiology of animal/human tissues much closer than conventional two-dimensionally plated cells. Some examples include multicellular spheroids formed by cancer and/or normal cells, stem cell organoids, endothelial tubes, bronchial outgrowths, bone and cartilage equivalents and retinal organoids. Important questions to be addressed by this objective include:

- How do the mechano-sensory mechanisms of differentiated cell/tissue models function in microgravity?
- How does the extracellular matrix affect gravity-related responses of cells and tissues?
- How does a proper cell differentiation influence cellular responses to gravity alterations?
- How does gravity shape tissues/organs and organisms?

Objective A.3: Evaluating the effects of altered gravity on epigenetics, genetic protection and repair mechanisms.

Gene expression studies are indispensable for investigation and elucidation of molecular mechanisms regulated by altered gravity. From previous studies, it can be assumed that epigenetic mechanisms are at least involved, if not a major factor in the regulation of gene expression by gravitational forces. Epigenetic modifications could possibly not only help to adapt the individual organism to altered gravity, but could represent also a very basic mechanism of adaptation during the evolution of life.

Experiments with cancer cells conducted in microgravity are also a hot topic. It has been shown that exposure to microgravity alters key biological processes, such as apoptosis and proliferation, that are relevant to cancer research. Spaceflight experiments have delivered first data showing that poorly differentiated thyroid cancer cells seem to redifferentiate in microgravity and further investigations are ongoing.

Important questions in this area include:

- Which genes are regulated by epigenetic mechanisms in response to microgravity?
- How are the genetic mechanisms responsible for tissue repair affected by gravity alterations?
- How does microgravity affect cancer cells and carcinogenesis?
- How do altered gravity conditions affect gene expression, proliferation and differentiation of stem cells?

Objective A.4: Investigating stress response induced by altered gravity conditions and possible countermeasures.

In skeletal muscle, mass and force are strongly reduced due to mid- and long-term exposure to microgravity. Oxidative stress generated by altered gravity conditions is deemed to be one of the main reasons for these muscular alterations. On the other hand, a deficit in reactive oxygen species production can hinder the destruction of incorporated microorganisms by macrophages.

Bio-compatible materials, such as nanomaterials, can provide protection against a number of detrimental effects observed in cells and tissues exposed to altered gravity and can represent highly efficient tools for counteracting free radical overproduction in cells, tissues and organisms during permanence in space. This objective will address important questions such as:

- How does gravity-induced oxidative stress affect cell differentiation and structural properties?
- What are the key processes of ROS production modified by microgravity?
- How can antioxidant defence mechanisms be improved by biomaterials and/or nutraceuticals?

Objective A.5: Understanding how gravity alterations affect other space-related physiological responses.

Previous space experiments and ground-based microgravity simulation studies have produced controversial results regarding the influence of microgravity on the repair of radiation-induced damage. This objective aims to address:

- Are the effects of gravity alterations on radiation-induced damage additive, synergistic or antagonistic?
- Does microgravity change the enzymatic repair kinetics of DNA damage induced by radiation?
- Does microgravity alter cellular radiation response leading to different outcomes such as cell survival, different forms of cell death, mutations, differentiation, senescence, chromosomal aberrations or transformation?

6.4.2. Question B - How Do Gravity Alterations Affect Animal and Human Systems at a Cellular/Tissue Level?

Bone, muscle, immune and cardiovascular systems undergo deep anatomical and functional modifications under altered gravity conditions. For example, the activity and differentiation of the bone-forming osteoblasts is decreased when they are exposed to simulated microgravity, while skeletal muscle mass and force are strongly reduced due to mid- and long-term exposure to microgravity, and all compartments of the immune system have been shown to be affected by spaceflight, most of the time negatively.

A fully functional immune system is of very high importance for any higher organism that is sent to space, not only due to its function against infections but also for its involvement in wound healing and cancer defence. All compartments of the immune system are affected by spaceflight, most of the time negatively (see Guéguinou et al., 2009 for review), although the involved cells are seemingly not directly affected by gravitational forces such as muscle or bone would. No conclusive mechanistic explanations have been given so far. Immune cells present the advantage that their precursors can be obtained and purified from bone marrow, while mature cells may be isolated from blood.

More recent studies have highlighted the fact that other human tissues/systems are also significantly affected by gravity. The lung parenchyma and bronchial mucosa, the skin and connective tissue (in particular during the wound healing process), the retina and the nervous tissue (especially at the neuro-muscular junction) have all been shown to undergo significant alterations following exposure to modified gravity conditions.

Objective B.1: Studying the effects of microgravity on the immune system in human and animal models

Differentiation of immune cells from bone marrow cells is a continuous and crucial process that is influenced by microgravity. It is of outstanding importance to understand how the mechanisms involved in this differentiation are affected by microgravity. Very fast responses and lasting effects have been described, but no key component has been identified so far.

Until now, humoral immunity and antibody production have rarely been investigated in microgravity, despite their important role in immune defence. B-cell function and, in particular, antibody maturation (somatic hypermutation) should be addressed. The effect of altered gravity on microorganism phagocytosis by macrophages is also an important issue. Finally, modifications of the immune response may depend on the infectious agent, while the infectious agents themselves may respond to the altered conditions, both outside and within the infected organism. Questions to be addressed include:

- How does microgravity affect immune cell differentiation and maturation?
- How is the genetic machinery in charge of improving antibody affinity altered by spaceflight conditions?
- How is the regulation of macrophage and osteoclast activation affected by altered gravity and how do these cells functionally adapt after prolonged exposure to microgravity?
- How are the host recognition and defence systems influenced by gravity alterations?

Objective B.2: Studying the effects of microgravity on the skeletal system in human and animal models

Unloading of the skeletal system during spaceflight leads to bone loss due to bone resorption and a decline in bone formation, resulting in uncoupling of bone remodelling. Osteocytes, the differentiated osteoblasts embedded in the mineralized bone matrix, are considered as the mechanosensitive cells but their role in spaceflight induced bone loss is an emerging research field. On the other hand, recent evidence shows that the activity and differentiation of the bone forming osteoblasts is decreased when they are exposed to (simulated) microgravity. The underlying mechanisms of impaired differentiation may involve changes in cytoskeletal organisation and intracellular signalling, but thorough insight into the gravity responsive processes in osteogenic cells is not known. Important questions include:

- How is the gene expression profile of different types of osteogenic cells influenced by microgravity?
- Do changes in chromatin modifications permanently alter the behaviour of osteogenic cells exposed to microgravity?
- Are these genetic changes linked to alterations in cytoskeletal organization?
- What are the mechanisms responsible for tissue loss (e.g. osteopenia/osteoporosis and muscle degradation) in altered gravity conditions and how can they be countered?

Objective B.3: Studying the effects of microgravity on other key biological systems in human, animal and microorganism models.

Integumentary System. Even though the integumentary system represents a vital barrier against deleterious environmental factors, and plays a key role in fluid diffusion and in thermoregulation, the effect of space conditions on skin physiology has been little investigated. Recently, it has been shown that a prolonged exposure to space conditions may induce skin atrophy, deregulate hair follicle cycle, and markedly affect the transcriptomic repertoire of the cutaneous striated muscle panniculus carnosus.

- Wound healing mechanisms in microgravity are not well characterized, despite the likelihood that the increasing use of human spaceflight as a research and commercial enterprise raises the probability of traumatic injury in space. Important questions to be addressed by this objective include:What is the effect of altered gravity on structural and mechanical properties of skin and wound healing?
- What are the effects of gravitational alterations on the cellular mechanisms controlling tissue response to injury and the evolution-driven shift from parenchymal regeneration to stromal scarring and fibrosis?
- What are the mechanisms involved in skin loss/atrophy that can be affected by microgravity?

Nervous System. The absence of gravity is rapidly sensed in higher animals through the otic/inner ear system, however the possible consequence of this detection on other physiological systems is largely unknown. Moreover, known, relevant morphological changes at the level of the neuro-muscular junction (NMJ) following exposure to microgravity are the decreased number of synaptic vesicles and neurotransmitter content, degeneration of axonal terminals, reduced axonal sprouting and increased NMJ remodelling. However, although there are many studies that have investigated NMJ adaptations in spaceflight, studies addressing molecular mechanisms underlying the microgravity effects on NMJ are still missing. Obectives include:

- Are there physiological responses to microgravity that are mediated through dedicated gravity sensing organs?
- What are the molecular mechanisms controlling NMJ formation, stability and plasticity under microgravity exposure?
- What are the NMJ-specific genes whose expression is regulated by exposure to microgravity?
- Are the spatial distribution and timing of assembly of specific molecular players at the NMJ postsynaptic region affected by exposure to microgravity?

Respiratory System. Microgravity profoundly modulates expression of extracellular matrix (ECM), adhesion and profibrotic molecules in mouse lungs. However, we still know very little on the effects of gravity on lung cell differentiation and it is therefore essential to develop a basic understanding of pulmonary development and mechanobiology under space conditions in order to ensure the respiratory health of personnel involved in long-term space missions. Important questions to address include:

- How does gravity alter the lung structure and function at a molecular and cellular level, and what possible repercussions do these changes have on the respiratory health of flight personnel?
- What are the alterations caused by microgravity in the development and performance of the pulmonary epithelial barrier?
- What is the role of gravity in ciliogenesis at the molecular and cellular level in the bronchial mucosa?

DNA repair System. The combined effect of microgravity and radiation in particular on DNA and its repair mechanisms is widely discussed. Several experiments performed in space in the past hinted at synergistic effects, antagonistic effects or no influence, depending on the test system. In none of these past experiments in microgravity, were the investigation of the whole mechanisms from damage induction to final repair performed. In particular during human space missions, both damage induction and repair will take place. In addition, results are important for maintaining microorganisms in space in bioregenerative life support systems (BLSS). Therefore, the whole pathway needs to be investigated, starting with microorganisms as model systems.

- Microorganisms. Microorganisms are crucial members of the environment and the human body, about 90% of the human body cells are microbes. They have important roles and are necessary factors for human health and well-being. However, we still know very little on the effects of gravity on microbial behaviour. Only a few studies report the increased virulence of certain microorganisms under microgravity conditions. Understanding the adaptation of microbes towards the changed environmental conditions in space is crucial for the proper maintenance of the human habitat and health of the human body.
- How do microorganisms react to space- and spaceflight conditions (increased virulence, active DNA repair mechanisms...)
- How do they adapt to space conditions? (increased extremophily, increased resistances against stresses)

6.4.3. Question C - How are Plants Affected by Altered Gravity, Either as a Stand-Alone Factor or in Combination with other Factors within the Space Environment?

Recently, an edible plant has been successfully grown as a result of the “Veggie” experiment on the ISS and used for food by the crew. Other experiments, using model plant species, have also succeeded in achieving an entire life cycle in space. Consequently, some adaptation or acclimation mechanisms should operate, such that, between the severe damage observed in early development and the robust and viable adult plants there must be a process of adaptation or acclimation. This means that important modifications at the cellular and molecular level do not result in later substantial changes at the developmental level, affecting the whole plant. Simple unicellular systems sense the absence of gravity, changing their cytoskeletal organization and the signal transduction pathways, while plant and animal development proceeds unaltered in these conditions, in spite of the fact that these processes are heavily involved in embryogenesis. Within the field of evolutionary developmental biology, results from long-term experiments using plants on the ISS may solve this apparent contradiction between unicellular organisms/animals and plants. Higher plants are complex multicellular organisms where different processes, involving cell proliferation and differentiation, occur throughout the plant life in different organs; regulation mechanisms can act at different levels (i.e. cell, tissue and organ).

Plant sensitivity to environmental factors, including those found in space, can vary at various life stages (e.g. dry seed, seedling, adult plant). Even within the adult plant, there are tissues and processes more vulnerable than others to the action of hostile factors because they are in the active growth (e.g. apical meristems) or reproduction phases (e.g. pollen and ovules). The apparent and yet unresolved paradox of the finding of important modifications at the cellular and molecular level which do not result in later substantial changes at the developmental level, affecting the full organism, is not exclusive of plants.

The objectives should be addressed using different biological plant model systems (e.g. *Arabidopsis thaliana* and selected crop species) integrating all results where multidisciplinary methodologies are applied: mt structure and eco-physiology.

Objective C.1: Understanding the fundamental ways that plants sense and respond to gravity alone or in combination with other space factors.

Different elements of plant growth and development can be identified and defined in order to study their changes under altered gravity, space environmental conditions. Among these elements, we could mention here:

- Gravitropism: perception of the mechano signal, transduction (intracellular, intercellular, intertissular) and response.
- Phototropism: identification of new phototropic responses in space, effects of different light quality.
- Cell proliferation and cell cycle (meristematic activity).
- Cell differentiation, including cell wall development, histogenesis and organogenesis.
- Processes of liquid and gas exchange throughout the plant.

For the study of these elements, the combination of microgravity with other environmental space factors, such as ionizing radiation, should be taken into account.

Objective C.2: Studying the long term effects of altered gravity and other space environment factors on plants and understand how plants adapt to that environment.

The plant adaptation and acclimation processes, responsible for the capability of plants to achieve their entire life cycle in space, producing essentially viable adult individuals, are important for our fundamental understanding within plant biology and especially because plants are to be used as food for crew and part of a bioregenerative life support system. In order to achieve a full understanding of this adaptive process it will be necessary to differentiate the short- to the long-term response of plants, by means of:

- Developing sequential studies involving the growth of plants after different times of exposure to space conditions and/or at different phases of development. These studies will determine molecular, cellular, structural and physiological parameters exhibiting a differential response, with respect to the time of exposure, to altered gravity in combination with any other factors of the space environment (e.g. ionizing radiation).
- Focusing on gene redundancies known to exist in plants and detecting differential responses of the redundant genes to changing environmental conditions. These gene redundancies contribute to the plasticity of plants in their survival strategies in a variety of environments throughout evolution.
- Studying the development of the water transport system and of photosynthetic organs, as they affect water transport and gas exchange. These factors will be implemented in the functioning and productivity of the whole plant in terms of regeneration of resources in bioregenerative systems.

Objective C.3: Studying primary and secondary effects of altered gravity on plant growth and development.

Reduced gravity prevents buoyancy-driven thermal convection in the physical environment around the plant that again has secondary effects on plant growth and development. The mass transport and exchange of gases and water and small molecules such as ions become diffusion limited, unless there is some forced flow or movement. These indirect effects can cause altered transport and exchange of gases and liquids between the plant and its surroundings. In this way the uptake of water and nutrients via the transpiration stream is affected. The cultivation facilities implement countermeasures for this indirect effect by e.g. forced convection with constant airflow in the cultivation chambers. However, the indirect effects need to be fully understood and taken into account as part of space experiment results. Within this framework, it will be challenging to:

- distinguish between direct and indirect effects of altered gravity on specific endpoints related to processes involving gas and liquid exchange such as (but not limited to): a) the dynamics of gas exchanges at the leaf level (which affect the efficiency of photosynthesis and respiration); b) the organization and functioning of the 3D water transport pathway from root to shoot; c) the dynamics of water and nutrient absorption.
- evaluate the possibility to modulate other environmental factors within the growth chambers to counteract and minimize the secondary effects of altered gravity. Threshold doses of such factors, and combinations between different factors, could be identified under which secondary effects can be disregarded.

Objective C.4: Investigating the interaction between microorganisms and plants (beneficial and pathogenic) under space conditions.

Although the effect of microgravity on living organisms have been identified, very little is known on how microgravity may impact those cellular interactions between mutualistic, symbiotic or pathogenic microbes and their hosts. Understanding how cellular interaction between two different organisms (plant/bacteria/fungi) under altered gravity conditions could help to improve our ability to induce symbiosis and a subsequent improvement on plant growth. Important questions include:

- Do gravity-related alterations in plants and microorganisms modify their relations (from synergistic to antagonistic and vice versa) or strengthen them?
- Do secondary effects of altered gravity affect the type of relation between plants and animals?

6.4.4. Question D - Microbiology and Microbiome

Microorganisms are everywhere, and are necessary components of our environment and our body. Only a very few of them could possibly harm us, most of them are necessary for e.g. proper digestion of food and the production of necessary compounds, such as vitamins. However, current flight experiment data indicate alterations in microbiome composition of environment and body, potentially going along with increased microbial virulence and decreased astronaut immune function during spaceflight. Nevertheless, a beneficial community of microorganisms is critical to maintain human health, but much deeper knowledge is needed with respect to the potential impact of spaceflight conditions on the environmental and human microbial community. Further knowledge and novel ideas to monitor and control the microbiome and pathogenic infections are needed, in order to avoid risk for human health, to maintain crew and spacecraft safety, but also for planetary protection issues.

Objective D.1 (Model) microbes and microbial communities

This addresses the response of model microorganisms and model microbial communities to space- and spaceflight conditions - Quantitative and qualitative assessment of the impact of spaceflight-induced alterations on microbial model strains and communities, using e.g. OMICS technologies. Selected model strains and communities of a broad spectrum (bacteria, archaea, fungi) should be evaluated, including (opportunistic) pathogens and beneficial microorganisms, such as probiotic strains. To address this it will be necessary to:

- Analyze alterations in microbial virulence (e.g. infection capacity, resistance against chemical/physical stresses, expression of resistance genes, changes in physiology, growth rate, morphology) during/after exposure to space and spaceflight conditions.

- Analyze structural, compositional, cellular and molecular alterations in material/microbe and microbe/microbe interactions during/after growth in/ exposure to space and spaceflight conditions
- Analyze the impact of space and spaceflight conditions on specific host-microbiome communities, such as (edible) plants and their microbiomes
- Analyze mechanisms of microbial resistance response towards antimicrobial treatments (e.g. exposure to antifungals and antibiotics) and decontamination efforts of relevant microbial species under space and spaceflight conditions

Response of viruses/phages to space- and spaceflight conditions:

- Analyze the impact of space- and spaceflight conditions to viral/phage- interactions with human cell lines or microbial hosts

Objective D.2. Microbial habitat management

Microbial dispersal and distribution in a space habitat: Analyze the microbial community of different areas and surfaces within the ISS, with respect to diversity, structure, quantity and distribution pattern, using cultivation, microscopy and molecular methods, such as OMICs technologies. This includes the detection of biofilms, and/or particle-associated microorganisms. The results should be systematically compared to suitable ground-controls in order to estimate the impact of space- and spaceflight conditions.

- Track microbial “contamination” routes from uploaded material (or new instruments/modules) to human crew and ISS environment, and vice versa
- Detect and analyse biofilms, addressing the concerns of bio-fouling, material-degradation or human health issues and identify potential hotspots for risk estimation

Decontamination and antimicrobial treatments. Evaluate currently used and novel decontamination methodologies, and develop methods for microbial bioburden control to meet microbial decontamination requirements under spaceflight conditions. To address this it will be necessary to:

- Develop (novel) antimicrobial surfaces and materials down to the nanoscale for spaceflight hardware design
- Develop and/or test biofilm-resistant materials down to the nanoscale that are able to indicate and inhibit the presence of multispecies biofilms

Microbial monitoring: Improve environmental microbiology monitoring for air, surfaces, water, and food during spaceflight and identify the microbial risk limits for future mission scenarios (microbial monitoring with emerging technologies for current and future mission scenarios)

Objective D.3. Human microbiome

Microbiome: risk for crew health. Monitor the impact of the human microbiome on habitat (surfaces, air, etc.) and possibly other crew members, assess associated health risks to advise future risk reduction strategies. To evaluate this it will be necessary to:

- Perform parallel evaluations of both the crew and vehicle microbiota to gain a better understanding of the changes that occur in the spaceflight environment and the implication to crew health
- Evaluate the potential risk of habitat microbiota on human health and: determine the efficiency of current countermeasures, evaluate the need for new countermeasure methods and applicability thereof, evaluate the presence of medically-relevant microorganisms and their virulence and resistance potential, define biomarkers as indicators for potential risks for crew and environment

Human microbiome: impact, modulation, optimization. Understand the type and mechanisms of adaptation of the human microbiome to spaceflight conditions (gut/skin/oral microbiome) on DNA, RNA, protein or metabolomic level, with major focus on medically relevant microorganisms, in comparison to appropriate ground-controls. It will be necessary to:

- Perform robust studies investigating the link of spaceflight (including diet), on microbiome and human health
- Investigate the potential support of human health using pre- and probiotics of different type and sources

6.4.5. Question E - How to Obtain an Integrated Picture of the Molecular Networks Involved in Adaptation to Microgravity in Different Biological Systems?

Progress in biology technologies has led to tremendous advances in large-scale data acquisition concerning cellular function (transcriptomics, proteomics, metabolomics and genomics). To date, -omics analyses have been successfully performed on various biological systems and have led to identification of genes and pathways involved in microgravity sensing and adaptation. Ultimately, to come to a global understanding of the molecular events that are triggered by altered gravity at a whole organism level, modern pathway analysis and construction tools will have to be used. The putative existence of (a) common pathway(s) may be revealed by comparison of the effects on various cell types of the same system, while adaptations specific to certain subsystems (muscle, bone, nervous system, B-cells) may be identified. In combination with fast methods of on-line live sensing and imaging methods, a complete picture of the processes involved during the process of adaptation and in the steady-state level in long-term flight can be obtained. Genome-wide analysis will also allow determining whether gravity effects follow a continuum from microgravity to hypergravity, or whether these two extreme situations represent different stresses compared to earth gravity. Finally, in addition to the primary response to microgravity, the secondary response upon landing on Moon or Mars (or return to earth) still remains a barely investigated topic.

Based on these considerations, it should be noted that some instruments/infrastructures such as bioreactors with on-line sensors and detectors, miniaturised and fluorescent microscopes, air-liquid interface- and long-term culture-capable incubators, lab-on-chip technology, enhanced transfer equipment are already under development and have a high TRL. These should be implemented for in-flight experiments, as well as for ground application, in order to optimize and enhance the quality and validity of future space research.

Objective E.1: Comparing different types of cell in the same organism and/or a single cell types in different organisms through the application of -omics approaches.

To date, whole genome approaches studying intracellular responses, activity of signalling pathways, and production of signalling molecules in altered gravity have been performed either on a single cell type, or on a whole organism. However, to fully understand the processes of adaptation to microgravity occurring in animal (including human) systems, cells need to be considered in their natural environment where they are communicating with each other. Studies on whole animals, realistic cell aggregates or organ-sharing programmes should be encouraged, as well as comparative data sets in different species to identify common, generalized responses. Important questions include:

- What are the genes and pathways affected by altered gravity in different cell systems and organisms?
- What are the intercellular communication pathways that are triggered in pluricellular organisms, and how do other cells respond to this?
- Are there common pathways operating in many cell types, and which pathways are specific to certain cell types?

Objective E.2: Using bioinformatics modelling (calls for new partners) for developing hypotheses concerning genes and pathways involved (common to entire organism or specific in individual systems)

The limit to spaceflight biology is often the limited availability of experimental replicates required to achieve statistically significant results. This is especially true for genome-wide expression analysis or proteomics studies, where the problem of extracting significant hypotheses is often solved through meta-analysis of different datasets. We propose to tackle these fundamental issues by three main actions:

- Increase statistical relevance by meta-analysis, construction of a database with the raw data and meta data of all the spaceflight experiments and ground experiments relevant to the biological problem addressed,
- Acquire time course measurements on the dynamic processes investigated integrating different datasets,
- Apply topology-based pathway analysis, and dynamic modelling, integrating causality in the reconstruction of the hierarchy of regulation.

Objective E.3: Real time analysis by online measuring of identified pathways

Many data obtained in spaceflight are based on single time-point experiments. Real time analysis, e.g. by live imaging has become an essential tool in life sciences that renders the biological dynamics in cells and organisms accessible, therefore enabling a better and more complete view of the complex adaptation processes induced by gravity alterations at all timescales. However, performing microscopy in space demands fulfilling specific requirements: a fully automated compact and lightweight imaging system is required that needs to be remotely controllable, with extreme mechanical stability, capable to withstand the vibrations of the launch without misalignment of the optical parts. Important questions include:

- How are the kinetics of cell adaption processes affected over several cycles of normal and altered gravity?
- How are the morphological characteristics of dynamic cell processes, such as diapedesis and phagocytosis, changed during spaceflight?
- How can deleterious events in cell/tissue cultures or organisms, such as infection by microorganisms or cell death, be countered on board?

6.5. Available Flight and Ground Platforms that Can be Used to Address Roadmap 4 Objectives.

A successful spaceflight/microgravity science programme cannot exist without a solid ground-based research foundation. Real spaceflight experiments need to be supported and prepared with on-ground studies using centrifuges and microgravity simulators like clinostats, random positioning machines and levitating magnets to extend existing data, test and validate transgenic models, or perform screening tests for countermeasures. It is highly recommended to continue and even increase the efforts regarding ground-based research. If applicable regarding response time, also drop tower, parabolic flights and sounding rockets should be used. When available, the sub-orbital platforms, such as ESA's Intermediate eXperimental Vehicle (IXV) should also be used. The great majority of experiments on animals will require just small adaptations of existing hardware. As far as ISS facilities are concerned, most of the experiments on animal and cell/tissue models can be performed already with KUBIK; other ones may require EMCS and BioLab facilities. For a timeframe up to 2024, non-ISS studies and related facility and hardware developments should be considered using free flyers such as the Russian Bion/Foton satellites or a commercial system like the DragonLab. ESA should make access to their and NASA's ground facilities easier and cheaper.

ROADMAP 7: SUPPORTING LIFE IN HOSTILE ENVIRONMENTS

7.1. Introduction and Background

7.1.1. Current State of Knowledge in the Subject Area

In the general context of sustaining human space exploration, there is a common agreement on the need for the integration of different disciplines and approaches to achieve a deep knowledge of biological processes in closed ecological systems, also in the presence of space factors (e.g. altered gravity, ionizing radiation, atmospheric pressure and magnetic fields) and develop new technologies for the realization of an artificial food chain where producers, consumers and degraders perfectly interact (for examples, ref.to Bamsey et al. 2009; NASA 2010; THESEUS roadmap 2012). For this purpose, international space agencies have invested resources to develop bioregenerative components and systems incorporating biological elements involved in the synthesis, purification and regeneration of basic life support commodities. Long-term human space exploration missions require a life support system capable of regenerating all the essential resources for survival. All components of Closed Ecological Life Support Systems (CELSS), based on living organisms and physical-chemical processes, need to be harmonized to achieve a safe, self-regulating, and chemically balanced environment for humans. The driving elements for the design of an ideal regenerative life support system are (i) the production of O_2 and biomass with high nutritional value, (ii) with the direct use of light as a source of energy for microbiological and plant biosynthesis, (iii) with limited O_2 consumption, (iv) in an easy to handle compact reactor setup adapted for spaceflight, (v) allowing an efficient and biosafe re-conversion of waste, CO_2, and minerals in simplified recycling steps, (vi) preferentially using, but not limited to known and already studied organisms that (vii) preferably possess a certain degree of 'space robustness'.

To date, a stable environment has not been achieved in ground-based demonstrators and testbeds developed in various countries [e.g. Russia's BIOS-1, 2, 3, and 3M, NASA's Bioregenerative Life Support Systems Test Complex (BIO-Plex), Japan's Closed Ecology Experiment Facility (CEEF), and Biosphere-2 in the U.S.]. Until now, many CELSS containing different types of biological elements (e.g. microalgae, higher plants, fish, microorganisms) have been proposed (Paradiso et al. 2014). An example is the Micro-Ecological Life Support System Alternative (MELiSSA) programme of ESA, which is aimed to develop a CELSS that will provide fresh food, oxygen and potable water from organic and inorganic waste recycling during long distance space exploration. It is based on five compartments including microbial cultures in bioreactors, a plant compartment and a human crew

(Photo)bioreactors are especially well suited to grow (photosynthetic) organisms for food, waste treatment, and production of biomaterials from a wide range of polymers. Micro-algal bioreactors for instance, are well studied with over 60 years of data and high production rates have been documented for many microalgae species. Possible outputs includes proteins, sugars/carbohydrates, lipids, nanostructures (for algae with exoskeletons) as well as clean water and O_2 as by-products. For more detail on bioreactor uses for biomaterials see the recent ESA project: "Sustainable Materials Concept", Appendix 1 to AO/1-7707/13/NL/RA.

In general, one could conclude that spaceflight has been shown not to hinder bacterial growth, on the contrary, it can enhance the growth of planktonic bacterial cultures, possibly through its influences on fluid dynamics. In addition, cyanobacteria like *Arthrospira* have been reported to be more efficient in fixing carbon and producing oxygen than trees while being an essential food supplement. Higher plants are also promising biological regeneration components which can also furnish fresh food, consume carbon dioxide and provide potable water from the collection of transpired water. Higher plants can adapt to extreme environments on Earth, and model plants have been shown to grow and develop through a full life cycle in microgravity. Moreover, plants are more resistant to ionizing radiation than animals: specific doses of radiation have been reported to stimulate some biological processes in plants (*hormesis*) such as increased seed germination, increased root growth and dwarf growth that is also desirable under conditions of limited volume availability in space. In addition, plants can also provide non-nutritive benefits and resemble effective countermeasures against deprivation in isolated/extreme environment. Moreover, since the plant's response to environmental factors is dependent on the genotype, the accurate selection of crops and cultivar within crops is fundamental to maximize resource regeneration and minimize waste. The latter can be achieved only if environmental and cultivation factors are maintained at optimal levels and accurately controlled. Indeed, although complete life cycles (seed-to-seed) have been achieved in space, there is evidence for the difficulty in the set-up and control of environmental conditions in CELSS in space. Specific cultivation systems and the use of beneficial microorganisms would help in the final objective of not only achieving the completion of the seed-to-seed cycle, but also optimizing the use of resources, yields and quality of the fresh food produced). Indeed, there is still a lack of knowledge about the biological requirements of different crops under ecologically closed systems, especially in the presence of space factors.

7.1.2. Identify where there are Links or Inputs from other Roadmaps or Assessments

The link between this roadmap and roadmap #5 can be made through *in-situ* resource utilization (ISRU) which imply not only recovery of water but should be investigated much broader. It could for instance include investigations into the potential of rocks (regolith) as a source of oxygen to support microbiological processes (e.g. 40% of the moon rock contains bound-oxygen as e.g. silicates), or as substrate for plant growth (after physicochemical and/or biological treatments) or as shielding material. In the same way, the THESEUS roadmap (2012) also recommended to test CO_2 extracted from the Mars atmosphere for ability to support photosynthesis.

A great challenge traced in this roadmap will be to regulate the levels of environmental factors normally present on Earth (e.g. light, nutrition, temperature, water availability) to maximize growth (e.g. biomass, fruit and seed production) and physiological performance (e.g. respiration, photosynthesis, water transport) of microorganisms and plants in ecologically closed systems. Considering that, in space, microbe and plant response to environmental factors can be further affected by altered gravity and ionizing radiation, a better understanding of gravity- and radiation-related phenomena is needed to better achieve the harmonization of cultivation conditions in bioregenerative life support systems. Extensive information on the development of microorganisms and plants under space conditions will be provided from the results of the roadmap # 6 "Understanding gravity-related phenomena in cells and organisms".
It should be noted that the exchange of information between the two roadmaps will be undertaken in both directions. Thus, data from roadmap # 6 complement those of this roadmap. Although both aim to achieve plant growth in space, the two roadmaps differ for the general approach: roadmap #6 is mainly devoted to understanding evolutionary trends of plants in space as triggered by the possible alteration of gravity-related phenomena while this roadmap is mainly on plant productivity in controlled environments on ground and in space, and interaction between plants and other organisms in the food chain (e.g. humans as consumers and microorganisms as decomposers) in bioregenerative systems.

7.2. Top Level Key Open Questions

- Can bacteria (including beneficial microorganisms), micro-algae and higher plants maintain high productivity in low gravity?
  - What is the best configuration for a photobioreactor or a greenhouse on a space station? Is there an option to provide artificial gravity to those bioreactors in space?
  - Will the relationship between beneficial microorganisms and plants be maintained in CELSS under space conditions?
- What materials can be used for fabricating photobioreactors and greenhouses to reflect cosmic and UV radiation while transmitting visible and infrared radiation?
- Can photobioreactors and greenhouses produce bioproducts for food or manufacturing on space stations?
- Can these materials be recycled in a closed loop?
- Can identified microbe/higher plant early-stress signals be monitored and countermeasured in real-time in space?
  - Is it possible to develop miniaturised sensors and control modelling for use in the spaceflight environment?
  - What is the influence of gravity and/or each environmental factor on the regulation of microbial/higher plant: genome transcription-translation, including epigenetic regulation? Structure and physiology?
  - What are the best (and most sustainable) cultivation systems and technologies to maximize plant growth

- and productivity on ground and in space? There is a need to test and identify which are the best: substrates (including in-situ resources)? Lighting systems? Nutrient delivery systems? Species and cultivars?
- How environmental and cultivation factors can be harmonized to improve the nutritional quality of plant-derived-food (e.g. maximization of yield, improving the nutritional quality and reducing anti-nutritional factors)?
- What are the (species-specific) protocols and procedures to optimize resource use efficiency for plant cultivation in CELSS (also in the presence of space factors) based on the precise identification of growth requirements which change according to life stage (seed, germination, seedling, adult) or phenological phase (vegetative growth, flowering, fruiting)?
  - Can these procedures be monitored and adjusted in real-time after an automated and precise control of environmental/cultivation/growth parameters?
- What are the best technologies, both biological as well as physico-chemical, to treat waste material (including those from cultivation, i.e. non edible parts of plants) and recover the main elements to be reused in the biological synthesis of new material?
- Can biocompatibility of materials for safe contact with crew or for use in biological life support systems be improved for long-term use in a sealed environment?
- Can new functionalities incorporated in materials (e.g. flexible, transparent, surface tension control, biodegradable, resistant to sterilization, resistant to biofouling, etc) be incorporated in CELSS?
- Can “bio-inspired” materials be used for life support systems?
- What are the effects on biofilm formation in biofilm bioreactors?
- Can methods and procedures be developed to monitor and ensure the reliability and robustness of subsystems and the complete life support system at different operational conditions?

7.3. Relevance to Human Space Exploration Goals and Societal Issues

7.3.1. Support to Human Space Exploration

- High rates of photosynthesis in photobioreactors create supersaturated aqueous O_2, which can be degasified to create atmospheric O_2.
- Photobioreactors and greenhouses can use urea waste as a nitrogen source for photosynthetic organisms.
- Photobioreactors and greenhouses can concentrate CO_2 for photosynthetic assimilation into biomass.
- Plants provide fresh food and play a role in improving psychological conditions in the isolation of space. Improving habitability is crucial during long-term stays (from 6 months onwards).
- Bacteria can break down complex organic molecules into essential building blocks (CO_2, NH_4^+, NO_3^-, PO_4^{3-}, K^+, ...) for food production.
- Bacteria can produce materials for in-situ manufacturing of biodegradable products (e.g. bioplastics).

7.3.2. Relevance to Societal or Terrestrial Issues

- Life support (sub)-systems are relevant to domestic waste treatment and water and nutrient recycling, zero-emission technology, submarines, and isolated extreme environments.
- Synergies with biotechnological research and developments in agriculture, food production and processing, pharmacy, waste treatment for high valuable product recovery can also be highlighted.
- Biomaterials will likely be one of the major research areas in the next 50 years.
- Plastics and carbon fibres reinforced resins can be used and produced in space.
- Algae biofuel is an energy source and is an area of active research.
- The perception and general acceptance of recycled products (e.g., food products), produced directly from waste in only a limited number of steps, remains an issue which should be addressed at a collective social, psychological and educational level. Similar approaches could be valid for a larger number of topics, including GMO’s.
  - Many micro-algal products are already used in food supplements, cosmetics and fuel.
  - The role of higher plants in waste recycling is obvious but social awareness should improve
- To increase sustainability of plant production in controlled environments for better management of natural resources

(also in hostile environments on Earth) and for the reduction of pollutant emissions.

- To improve waste recycling processes in areas where anthropic pressure is high for the preservation of the natural environment and lower the impact of human activities.
- To increase process control, including automated technologies, in controlled cultivation systems to reduce production costs, improve production methods, and increase yields and profit.
- Safe sanitation and pathogen control in confined spaces and eco-districts/cities with short-cycling material flows.

7.4. Specific Objectives / Questions to be Addressed up to 2024

The support of human life in space relies on the optimization of the relations between different organisms and systems/subsystems. To achieve the goal of sustainable life support, an integrated approach to create synergies between different disciplines is needed to improve the knowledge about the behaviour of both biological and physical-chemical systems under environmental constraints of hostile environments (e.g. altered gravity, ionizing radiation, altered atmospheric pressure and magnetic fields). Top level objectives and specific sub-objectives are reported in the following scheme:

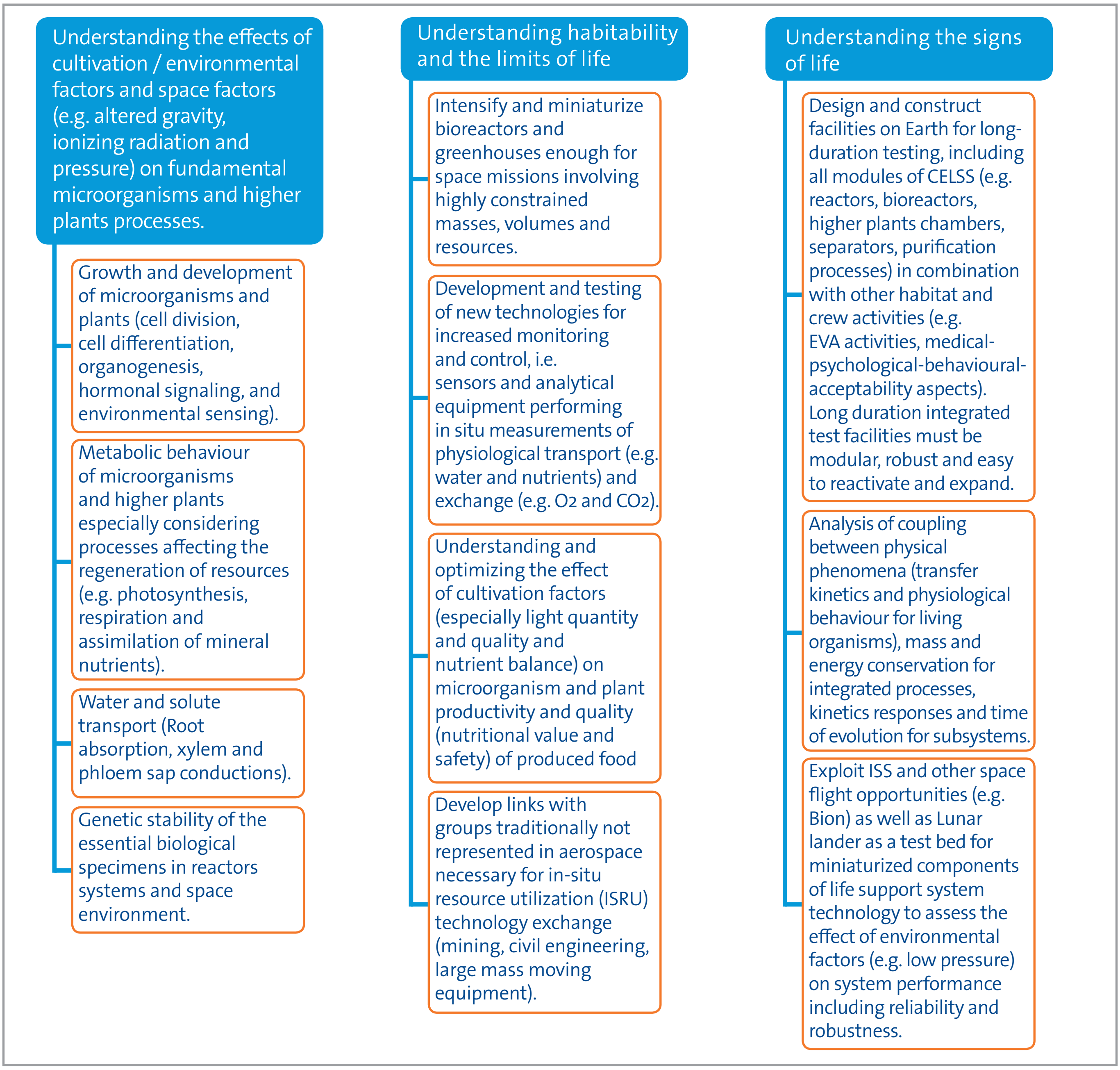

Figure 7.1. Specific objectives in Supporting Life In Hostile Environments

7.5. Short Discussion of how Available Platforms (Both Flight & Ground) Opportunities / Programme can be used to Address Roadmap Objectives

Russia has built the longest and strongest expertise over the last 50 years in long duration testing in integrated and confined habitats (e.g. BIOS facilities in Krasnoyarsk, IBMP facility in Moscow). Large scale integrated test facilities have also been built in JAPAN (e.g. CEEF), USA (e.g. Biosphere 2) and China (Lunar Palace) with variable success. Europe, however, has mainly relied on the Russian expertise through collaborative projects (e.g. MARS100, MARS500), and only recently initiated construction of its own facilities and independent investigations (e.g., utilization of Concordia station in Antarctica –, MELiSSA pilot plant in Spain and :envihab in Cologne. Thus, Europe still has a large potential to grow in this area and develop more expertise and facilities (THESEUS roadmap, 2012, http://www.esf.org/fileadmin/Public_documents/Publications/RoadMap_web_01.pdf).

Besides numerous available platforms including clinostats, rotating wall vessels, random positioning machines, drop towers, parabolic flights, sounding rockets and the Foton retrievable capsules, the best option for performing space experiments is considered to be on the ISS. Satellites, and to some extent parabolic flights, can be a good alternative to analyze the short-term effects of fractional gravity on plants for instance. Longer exposure to space conditions can be studied in low Earth orbit on the ISS with facilities like Biolab, EMCS and Veggie. The EMCS and Biolab allow for experiments with small biological systems under graded gravity levels with full environmental control, and can mimic the gravity conditions of Moon and Mars.

Regarding the simulation of ionizing radiations, Low-LET (Linear Energy Transfer) ionizing radiation (e.g. X-rays and gamma rays) is generally easily available in many universities and research centres like the Belgian Nuclear Research Centre, while facilities to produce High-LET ionizing radiation are available at GSI (Germany), GANIL (France), NARILIS (Belgium), LNS-INFN (Italy), PSI (Switzerland) and HIMAC in Japan.

ROADMAP 8: UNDERSTANDING AND PREVENTING PHYSIOLOGICAL ADAPTATIONS TO REDUCED GRAVITY:

8.1. Introduction and Background

The inputs received from the scientific community are unanimously based on the work performed in 2012 in the frame of the European Community's Framework 7 programme. The objective of THESEUS was to develop an integrated life sciences research roadmap enabling European human space exploration in synergy with the ESA strategy, taking advantage of the expertise available in Europe and identifying the potential of non-space applications and dual research and development. The key questions identified within the THESUES project have in essence not changed that much, but in the course of the elaboration of the human research roadmaps (Roadmaps 8 and 9) have been updated in the respective areas.

8.1.1. Definition:

- Understanding spaceflight-induced changes related to physiological systems and their underlying mechanisms and processes with the aim of elaborating effective countermeasures making use of ESA's ground-based and ISS platforms.
- Optimizing crew health and well-being including, but not limited to, physical training, rehabilitation as well as other preventative treatments.
- Understanding and ultimately transfer acquired knowledge gained in space (- simulation) studies to terrestrial applications.
- Ultimately enabling future human long-duration spaceflight missions beyond LEO

8.1.2. Background:

Mankind can look back on more than 50 years of human spaceflight experience, including both short- and long-duration missions on a variety of platforms. Medical and physiological findings from these missions have demonstrated that spaceflight has a dramatic impact on almost all physiological systems including, but not limited to, muscle atrophy, bone demineralisation, cardiovascular and metabolic dysfunction, impaired cognitive processes and reduced immunological competence, and nutrition/metabolism. These adaptive responses lead to a physiological de-conditioning in space and have the potential to affect crew health and performance both in space and upon return to Earth. In many instances, countermeasures have been implemented to mitigate some of the maladaptive changes associated with spaceflight, including drugs, nutritional supplements and physical exercise on various workout devices.

Although no countermeasures are able to fully mitigate the negative effects of spaceflight, several have proven to be very effective, allowing crew to live and work nominally on-orbit. European scientists have contributed largely to this knowledge database and acquired undisputable expertise in basic space physiology and countermeasures through both spaceflight experiments and a strong and complete ground-based programme.

8.2. Specific Objectives / Questions to be Addressed

Human spaceflight is currently entering the next phase of space exploration towards the Moon and Mars, and inherent medical challenges are linked with such ambitious goals. Knowledge regarding human (mal)adaptation to microgravity is limited to that obtained during 6-month missions, with the majority of information connected to short-term physiological changes. Therefore, the primary focus of the next phase of biomedical research will be to further expand knowledge on the effects of long-duration spaceflight on crew health and performance, to further develop efficient countermeasures and to facilitate post-flight readaptation to the terrestrial environment. Such basic and upstream research is clearly a pre-requisite for long-term spaceflight, interplanetary travel and living on planetary surfaces, and ESA's future Utilisation programme will contribute to that by addressing key research questions in the following areas:

A Heart, lung and kidneys

A.1.1 Fundamental questions in the cardiovascular area:
- µg-induced alterations in cardiac and vessel structure and function
- Molecular and cellular changes
- acceptable level of cardiovascular function loss

A.1.2. Exploration-relevant questions:
- Type and quantity of exercise required to maintain required level of cardiovascular function

A.2.1: Fundamental questions in the pulmonary system:
- Effects of gravity/gas density interactions on pulmonary function and outcome of clinical lung function tests
- Cellular and molecular changes

A.2*.2. Exploration-relevant questions:*
- Risks associated with extraterrestrial dust

A.3.1: Fundamental questions in the kidney system:
- Role of diet and bone demineralization on kidney stone formation

A.3.2. Exploration-relevant questions:
- Prediction of risk of kidney stones

B Bone and muscle

B.1.1 Fundamental questions:
- Effects of µg on musculoskeletal processes (ligaments, cartilage, intervertebral discs, tendons, bone fracture, back pain) and the role of gender and genetics on those processes
- Biomechanics and impact of µg on the musculoskeletal system
- Molecular and cellular basis for changes

B.1.2. Exploration-relevant questions:
- Optimization of countermeasure efficiency, including rehabilitation:
- Recovery after short- and long-duration spaceflight missions

C Immune system

C.1.1 Fundamental questions:
- Immune system development, response and regulation in space
- Identification and quantification of stress factors and their impact on immunity and its interactions with other organ systems

C.1.2 Exploration-relevant questions:
- Consequences of long-duration spaceflight missions on degree of immune suppression (in-flight and post-flight)
- Monitoring of immune dysfunction also referring to interactions to the environment (e.g. life support systems, habitat atmospheres, and lunar dust)
- Definition and testing of (targeted) countermeasures

D Nutrition and metabolism

D.1.1. Fundamental questions:
- in-flight negative energy balance, (micro)nutrients deficiency
- Fluid shift
- Feeding behaviour
- Metabolic stress, hydro-electric imbalance, peripheral insulin resistance
- Alterations of gut microflora
- Molecular and cellular basis for changes

D.1.2. Exploration-relevant questions:
- Optimization of diet regimes
- Countering consequences of fluid shift
- Countering peripheral insulin resistance

Figure 8.1. Specific objectives in Physiological Adaptations to Reduced Gravity

ROADMAP 9: PSYCHOLOGICAL AND NEUROSENSORY ADAPTATIONS TO REDUCED GRAVITY, ISOLATION AND CONFINEMENT

9.1. Introduction and Background

The inputs received from the scientific community are unanimously based on the work performed in 2012 in the frame of the European Community's Framework 7 programme. The objective of THESEUS was to develop an integrated life sciences research roadmap enabling European human space exploration in synergy with the ESA strategy, taking advantage of the expertise available in Europe and identifying the potential of non- space applications and dual research and development. The key questions identified within the THESUES project have in essence not changed that much, but in the course of the elaboration of the human research roadmaps (Roadmaps 8 and 9) have been updated in the respective areas.

9.1.1. Definition:

- Understanding spaceflight-induced stresses and related mechanisms and processes as well as countermeasures for psychological, neurosensory, neuroendocrine and stress-sensitive systems of the human body
- Optimizing crew selection criteria, crew cohesion and performance including, but not limited to, behaviour and performance
- Enhancing and optimizing the human factor contribution to space exploration missions' operations
- Ultimately enabling future human long-duration spaceflight missions beyond LEO

9.1.2. Background:

Exploratory missions to Moon and Mars including the establishment of a permanently crewed base on the lunar surface will add a new dimension to human spaceflight, taking into account the distance of travel, the radiation environment, the gravity levels, the duration of the mission, and the level of confinement and isolation the crews will be exposed to. The physical and psychological demands given by the long distance of travel, the duration of permanent living under dependence of automated life-support systems, the degree of isolation and confinement, and the lack of short-term rescue possibilities in case of emergencies will exceed those of anything else humans have ever been exposed to. This will raise the significance of several health issues, above all individual and crew performance, individual and crew well-being as well as sensorimotor issues, which are assumed to become a possible limiting factor to human adaptability during these missions.

In order to be able to protect astronauts from the negative effects of isolation and confinement, the factors that promote or threaten crew cohesion, individual and crew (sensorimotor) performance as well as individual and crew well-being need to be identified. Since the questions that need to be addressed are manifold and multifactorial, a structured step-by-step approach is proposed to retrieve valid and comparable data within a reasonable and realistic time frame. This approach aims at the development of tools to prevent performance, emotional, cognitive, and psychosocial degradation of the individual crewmembers as well as to maintain skills, crew cohesion and crew performance.
The European Space Agency has a long history in conducting and participating in isolation and confinement studies and substantial experience and achievements in assessing the risks for humans in the space environment has been gained. Nevertheless the currently available database is too small to derive definite risk assessments and further research is needed to assess the psychological issues associated with these missions in order to be able to develop appropriate countermeasures.

9.2. Specific Objectives / Questions to be Addressed

A Neuroscience

A.1.1: Fundamental questions:

- Impact of spaceflight and planetary surface stays on sensorimotor and neuro-behavioural performance and their decrement
- Understanding the role of gravity in the development of nervous system

A.1.2.Exploration-relevant questions:

- Countermeasure strategies to minimize risks associated with neurophysiological changes during and after g-transitions

B Psychology

B.1 Fundamental and exploration-relevant questions in the group and team processes area:

- Crew selection, building, training, crew cohesion, well-being and performance
-Systematic investigation of psychological, social, neurophysiological and immunological impacts of ICE
- Support methods, rehabilitation, re-socialization, re-integration

B.2: Fundamental and exploration-questions in the skill maintenance area:

- Risks for operational effectiveness from infrequent or non-use of skills
- Need for different training methods for the acquisition and maintenance of different types of skills; training versus refreshment versus new acquisition
- Protection against effects of stressors on skill learning and effective long-term skill performance Management of sleep and work/rest schedules to prevent skill impairment

Figure 9.1. Specific objectives in Psychological And Neurosensory Adaptations To Reduced Gravity.

ROADMAP 10: COSMIC RADIATION RISKS FOR HUMAN EXPLORATION OF THE SOLAR SYSTEM

Cosmic radiation is generally considered the main health hazard for human exploration and colonization of the Solar system. The main biological effects associated with exposure to cosmic radiation are carcinogenesis, late degenerative tissue effects, hereditary effects and acute effects after high dose exposure. Cancer currently dominates risk estimates, but non-cancer effects, especially central nervous system (CNS) and cardiovascular risks, are becoming an increasing source of concern. The major objective of space radiation research is to assure that during any mission the crew will be subject to as low of a radiation exposure as reasonably achievable (ALARA), enabling human exploration of the solar system within an acceptable radiation risk. The definition of acceptable dose limits for exploration is one of the main challenges for the design of the missions to Moon and Mars. However, radiation risk is characterized by a high uncertainty and lack of simple countermeasures. Most of the uncertainty on space radiation risk is associated with the poor knowledge of the biological effects of cosmic rays. This includes interaction of radiation damage with the effects of other space environment stressors, relative biological effectiveness (RBE) factors for energetic heavy ions for late effects, errors in human data including statistical, dosimetry and transfer between populations in application to space risks, effects of exposure to mixed high and low LET space radiation and the dose response curve at low radiation doses. Therefore, the objectives stated in this roadmap will address these points through experimental studies. The data to be obtained will improve the models which are necessary for a correct radiation risk assessment. In addition to supporting the needs of Human Space Exploration missions the information obtained is relevant to assessment of terrestrial risks due to low dose ionizing radiation exposure and improvement of charged particle therapy in oncology.

The goals of this roadmap are derived from Theseus Roadmap: Cluster 3 – Space Radiation. These objectives are described in detail in the Theseus report which can be found at
http://theseus-eu.ameos.net/fileadmin/Docs/Eg_reports_roadmap/Cluster3_web.pdf

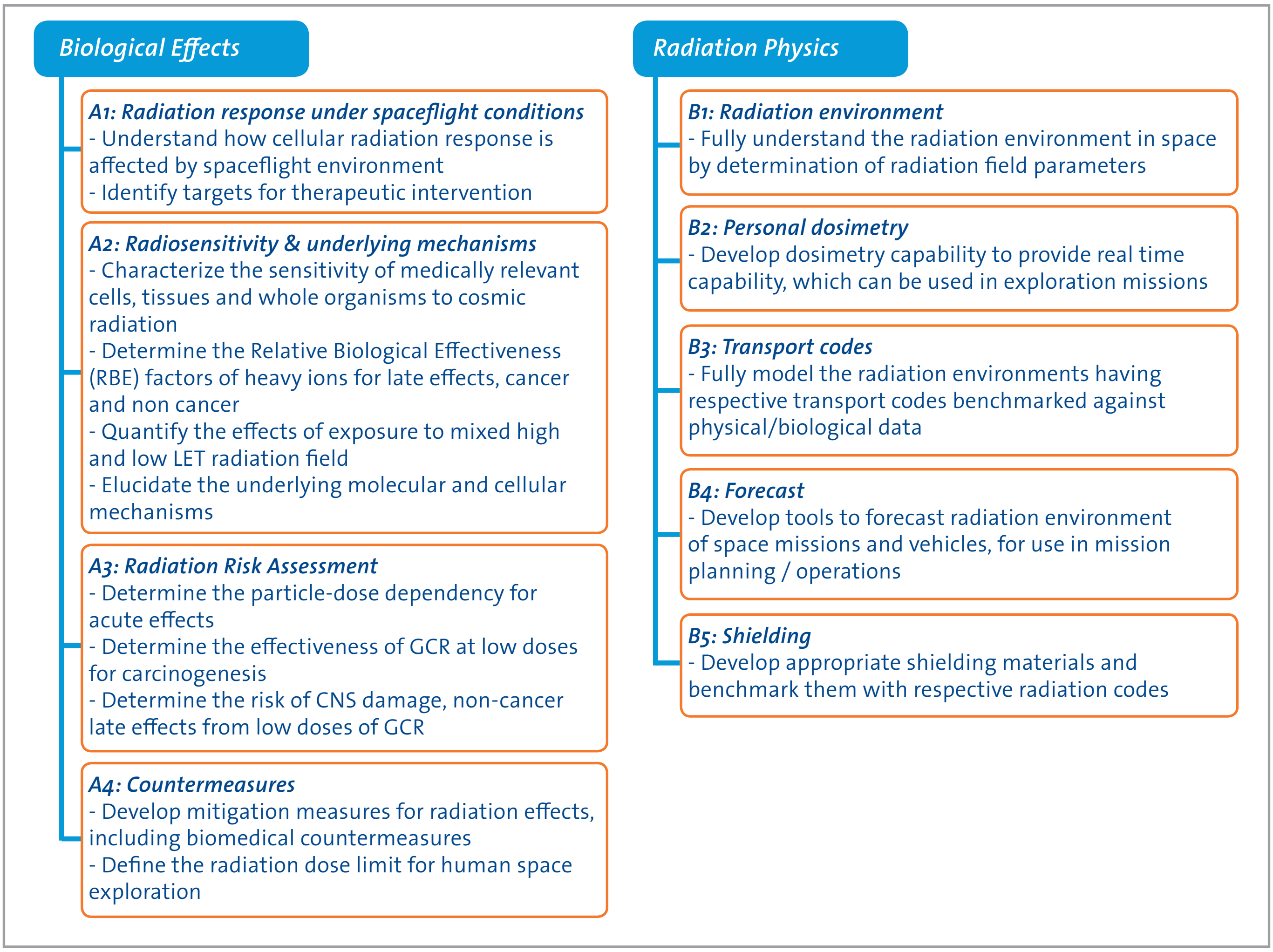

Figure 10.1. Specific objectives in Cosmic Radiation Risks for Human Exploration of the Solar System.

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