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February 1999

Exploiting the International Space Station

A Mission for Europe

Services
Research
Education
Applications

European Space Agency
Agence spatiale européenne

Directorate of Manned Spaceflight and Microgravity
Direction des Vols Habités et de la Microgravité

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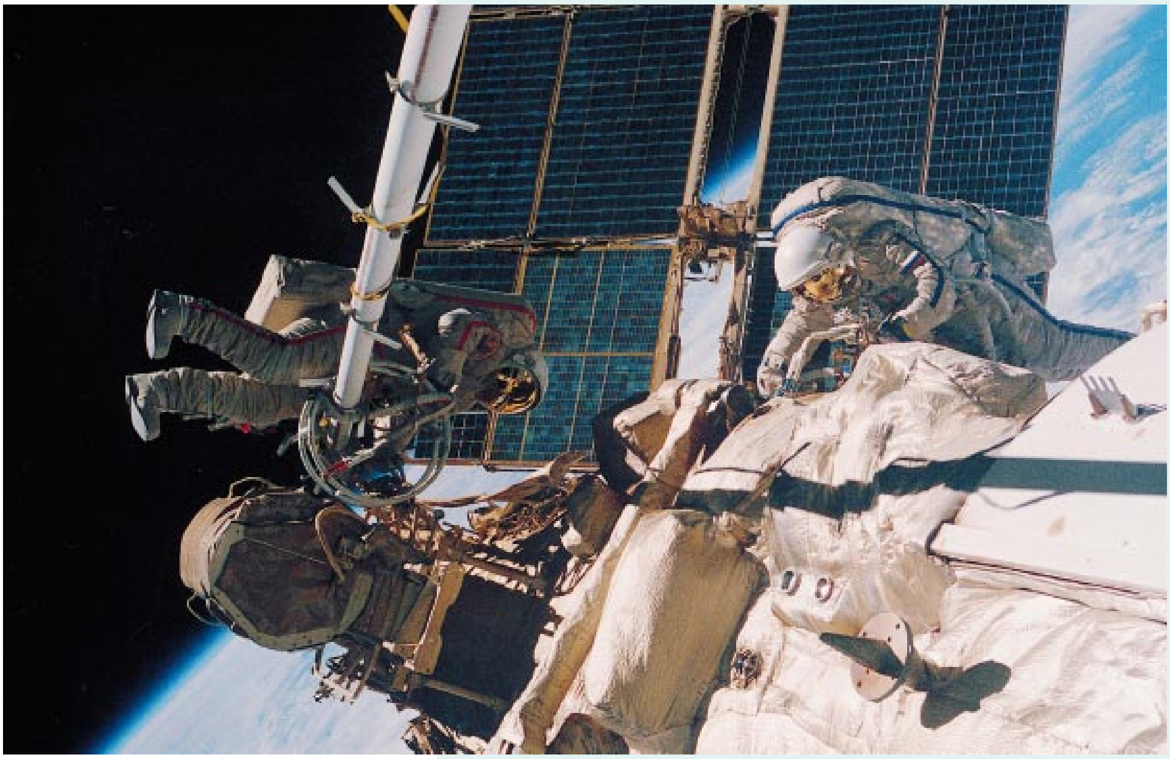


Further information on ESA and its participation in the International Space Station can be found at http://www.estec.esa.nl/spaceflight/

Foreword

The International Space Station is the largest space science and technology venture ever undertaken in human history. Its design and construction brings together technical and scientific teams from agencies and industry in the United States, Russia, Canada, Japan and the ESA member states. It is they who are working in close collaboration to turn the vision into the reality of a sophisticated laboratory in space with a permanent international manned presence.

That international collaboration is set to develop further and to strengthen as the Station enters service and the participating nations embark upon the extensive programmes of research and technological studies of the kind outlined in this document. Those programmes will come to involve the community of researchers worldwide, either directly as Station experimenters or indirectly as the data and understanding derived from the space experiments are applied to solving problems in on-going Earth-based research and industrial studies.

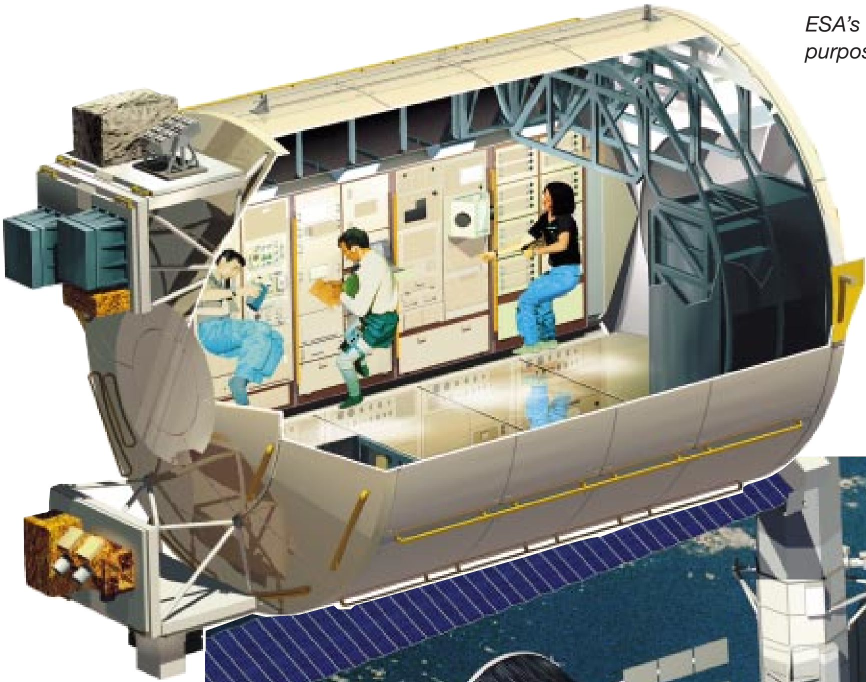
Whether those activities involve extending our fundamental knowledge or aim at improving industrial processes, whether they seek to improve human health and welfare or aid the further exploitation of the commercial utilisation of space, each will bring enduring benefits to Mankind. In so doing, it will mark the International Space Station as a milestone in our expansion into space and the application of space to the service of Mankind.

The European Space Agency (ESA) planning for Station utilisation is based upon a desire to link the more fundamental aspects of research to potential benefits in the public and industrial domains. At the same time, the Station's unique capabilities in manned support, ready access, servicing and the potential for massive resource applications have determined the selection of technological and scientific systems to be housed on external platforms for Earth and space observations.

The nature of the proposed ESA studies and activities, together with some of their potential applications and benefits, are outlined in this brochure, which has been prepared as a supporting document to the ESA Programme Proposal for the ISS Exploitation Programme. There is, of course, much more to be said in the detailed planning than can be covered in an overview such as this.

Nonetheless, I hope that by studying this overview the reader comes to share the excitement and interest as the International Space Station is being assembled in space and the opportunities for its utilisation open up in the years ahead.

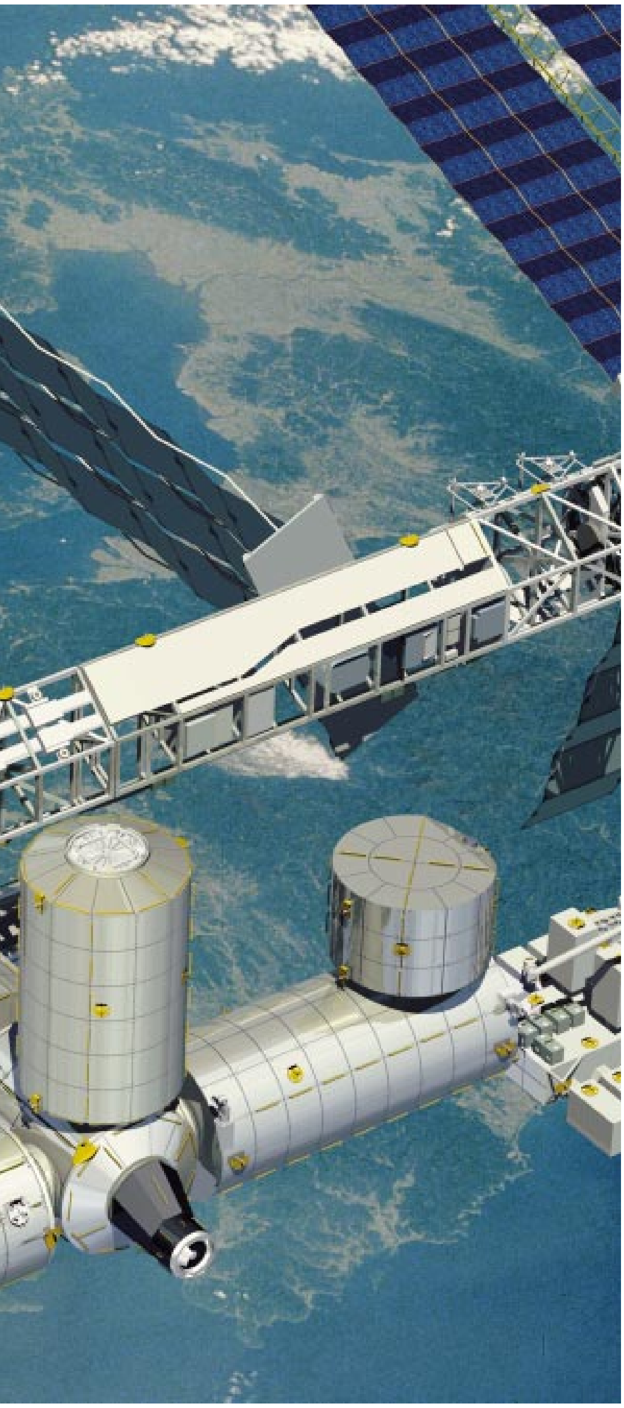
Jorg Feustel-Büechl
Director, Manned Spaceflight and Microgravity, ESA



ESA's Columbus module is a general-purpose laboratory. (ESA/D. Ducros)

The International Space Station as it will appear after completion in 2004. (ESA/D. Ducros)

The Space Station: An International Endeavour



The International Space Station (ISS) is becoming a reality. The first elements, from the USA and Russia, were launched into orbit some 400 km above the Earth at the end of 1998.

With increasing momentum, the build-up in space will lead to a fully operational Station, comprising the US, Russian, Japanese, Canadian and European laboratories and facilities, by the end of 2003.

With its completion, a new era in manned spaceflight will begin. The facilities available to Europe and the international community, both inside this 420 tonnes space laboratory and attached externally, exceeds the scope and sophistication of anything that has gone before.

Combining these large facilities and resources with the flexibility provided by regular access for equipment exchange and sample return, presents a unique opportunity for pure and applied research and for technology studies on a long-term and repeatable basis.

In addition, trained crews dealing intelligently with unforeseen and novel situations greatly extends the potential value and application of this new space system.

The International Space Station is unique not only for its range of facilities and the complexity and scale of the technical undertaking, but also for the extent of the international partnership required to make the concept of a large Earth-orbiting laboratory a reality. European space industry is working in close partnership with those of the United States, Russia, Japan and Canada, to design and develop the ISS, its facilities, and its supply and support systems.

This international partnership will continue to expand, with developing contributions from new industries and diverse technical and academic institutions throughout Europe.

The extensive use of experiments directly controlled and manipulated from Earth will simplify the research process and provide opportunities for a widening range of European scientists previously with limited experience of space experimentation. Such research facilities also offer challenging opportunities for European science educators to participate in experiments and demonstrations, possibly via low-cost Internet links with schools and colleges.

In the longer term, the construction, operation and exploitation of the Space Station by the international community will be seen as one of the major steps by Mankind in the continuing expansion into space. With a large permanently manned base and laboratory network, it becomes possible to sustain that expansion. Concerns such as the long-term effects on humans of exposure to the low-gravity conditions and radiation environment can be studied in depth. Likewise, the practical problems involved in creating closed-loop life support systems can be solved and the feasibility of recovering and regenerating waste materials put to the test. The Space Station will act as a testbed for addressing areas such as improved power conversion and storage systems, robotics, lower cost resupply vehicles and new information handling techniques.

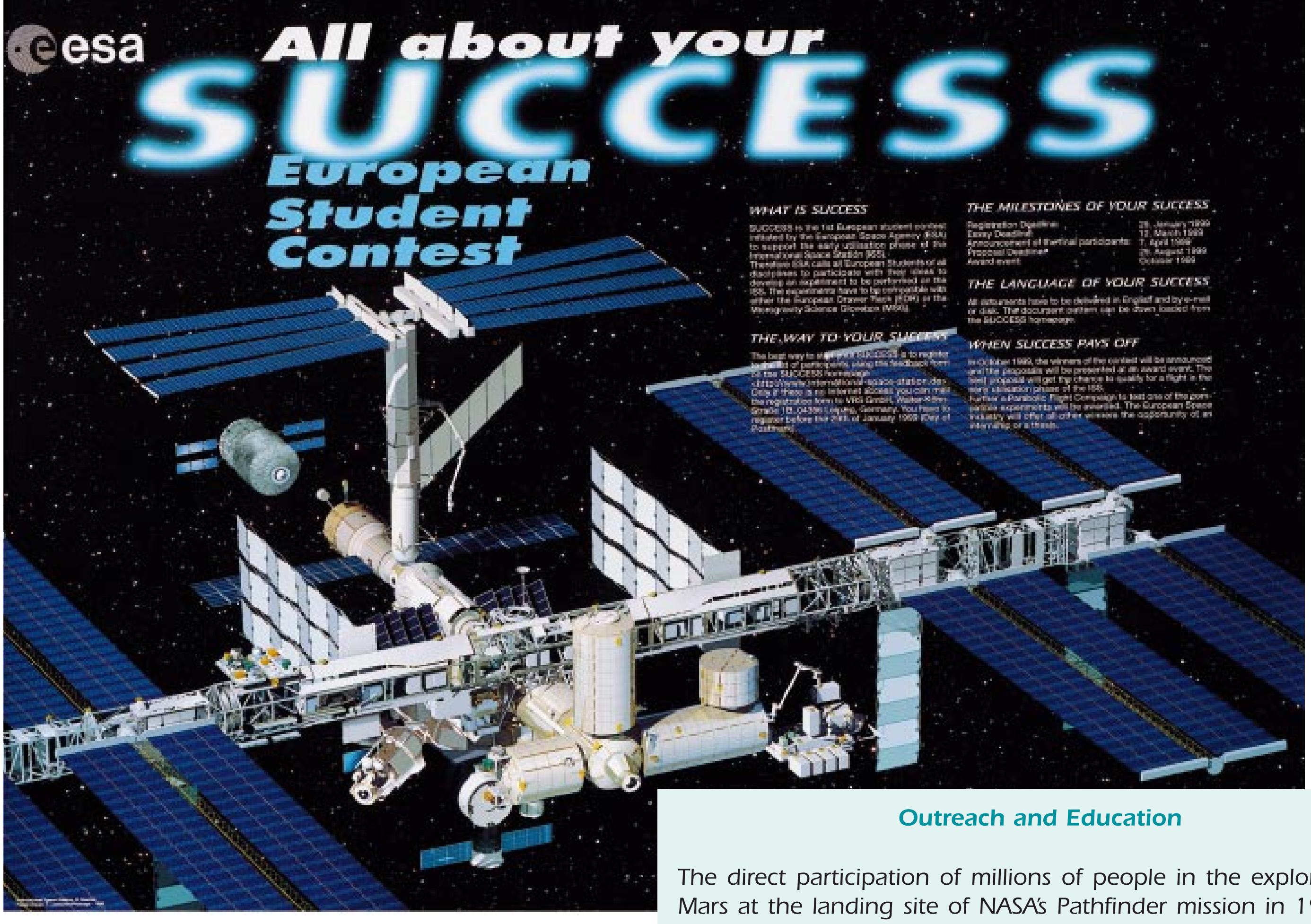
Research on the International Space Station will build on the foundations laid by experiments on the Mir space station, the Space Shuttle/Spacelab, the Eureca platform, sounding rockets and aircraft.

The successful exploitation of ISS facilities and opportunities by scientists, engineers and commerce will be an important development in its own right. Much of that activity will be concerned with the effects of gravity on biological, physical and chemical processes – fundamental concerns for everyday activities.

For example, combustion processes are strongly influenced by gravitational effects on the flowing gases. To fully understand them, we must, effectively, reduce the force of gravity. That can be done in the extremely low-gravity (microgravity) free-fall environment of the Space Station.

It will be possible, for example, to improve significantly the combustion efficiency of burners for domestic and industrial heaters, reducing pollution and cost.

The Spacelab/Shuttle, Eureca and Mir experiments in these fields, together with short-duration experiments on sounding rockets and aircraft parabolic flights have laid a solid foundation for future research aboard Space Station.



The leap forward offered by the ISS lies in the unique range and quality of its research facilities combined with the continuity of experimentation (duration and repetition). A good deal of that research will be directed towards creating applications and benefits on Earth.

In addition to the gravity-related research activities, the Space Station can accommodate extensive external equipment. Several tonnes of instruments can be located at various points on the structure. That means the ISS can be used as a technology testbed and can accommodate very large instruments for remotely sensing terrestrial and celestial targets. It is especially appropriate for instruments requiring frequent replacement of components (e.g. detectors) or replenishment of supplies (e.g. cryogens).

The following chapters provide overviews of Station activities, the nature and importance of the many research and technical projects, and their likely value in human terms.

Outreach and Education

The direct participation of millions of people in the exploration of Mars at the landing site of NASA's Pathfinder mission in 1997 was made possible by the imaginative use of the Internet. With unprecedented immediacy, people experienced the excitement and the difficulties of exploration. The media's easier and greater access encouraged even wider dissemination of information. It was indeed a pathfinder to Mars and to how space activities can be opened up and made interesting and relevant to the public.

In addition to involving the public directly in the drama of exploration, it is also possible to help them understand aspects of the science and technicalities by carefully using illustrative material and concise explanations. Such participation and education is a feasible and highly desirable goal – and will be pursued within the ISS utilisation programme.

Many Space Station experiments will be remotely controlled from Earth, using video and data links with the participating centres. It will thus be possible to observe selected experiments while adding explanations by qualified commentators.

This will provide an important extension of the Space Station public information programme. It opens up the opportunity for educational establishments at different levels to follow the progress of particular experiments and Earth or astronomical observations. Beyond lies the possibility of students and institutes proposing their own experiments, taking part in the preparation and execution. The wide range of Space Station facilities means that many types of student experiments could be performed without major investment.

As part of the ISS educational programme, ESA has established the SUCCESS contest inviting senior students to propose experiments for the Space Station. The winners, announced in October 1999, will be offered internships or thesis opportunities with European industry, and the best proposal will be considered for a flight opportunity. Further information on SUCCESS is available at http://www.international-space-station.de/

Living and Working Together in Space

European astronauts will form part of the Space Station's international crews. Once assembly is complete in 2003, up to seven astronauts will be aboard, charged with the demanding task of safely and efficiently operating and maintaining the Station, its laboratories and facilities. This calls for an environment providing crews with a healthy and relaxed life outside of work periods. Creating this in the confined and isolated world of the ISS for the several months' stay of each crew member is difficult. The problem is compounded by the effects of weightlessness on the human body.

Living and working together in space is not easy. It is a high-stress working environment, because the crew are always under pressure to maximise their output. It is also a risk-sensitive environment, where continuous vigilance and concentration are demanded. The crew are inevitably aware of their huge responsibility for safety and mission success.

Beyond these demands lies the influence of the low-gravity environment on the human body and mind. Microgravity presents the body with a new and strange world. The senses are confused as weight is replaced by inertial reactions, and the sense of touch is altered. Balance is disturbed, since it relies partly on gravity. The result is disorientation, often accompanied by nausea in the early days. Crew have to adjust to this strange world, where 'up' and 'down' no longer have any meaning, while working to a punishing schedule.

In those conditions, crews come to depend on each other and national differences are of little consequence. They will be truly an international team supporting an international endeavour.

It is becoming clear that microgravity perturbs not only the sensory system but the body as a whole. System functions, such as blood circulation, lung performance, fluid distribution and electrolyte balance, are modified as the body adapts. Fluids are freed from gravity's pull and density differences count for nothing.

Considerable research will be devoted to understanding these effects. This could benefit ground-based studies in Europe, because controlling gravitational effects can be a valuable additional probe of system functions.

Living and working in microgravity also appears to induce fundamental changes in the body down to the cellular level. Their full extent has yet to be elucidated. Again, they will be intensively studied.

However, it is already clear, for example, that the weight-bearing bones suffer progressive deterioration as the normal equilibrium of bone formation and resorption at the cellular level is

Astronauts and other biological systems experience accelerated bone loss in space. Microgravity provides an accelerated testbed for osteoporosis studies.

ESA astronaut Thomas Reiter performing maintenance work aboard Mir.

perturbed. Excessive bone cell resorption occurs and osteoporosis-like symptoms appear.

There seems to be no end point to this deterioration and the effects of very long exposure are serious. Limiting an astronaut's tour of duty aboard the Space Station to a few months will be the norm. At the same time, research into countermeasures will continue as a priority, since manned flights to Mars will entail long exposure to low-gravity conditions.

Results from this research will benefit Earth-based studies into osteoporosis, a disease that afflicts a high percentage of the elderly in Europe, with major consequences in terms of human suffering and medical costs.

Experience on Russia's Mir space station has clearly shown the importance of maintaining the physical health and mental well-being of the crew. Although the rigorous crew selection, training and pre-flight checks reduce the risk of serious in-flight problems, it is inevitable that some unexpected difficulties will occur, including accidents.

In order to deal with such problems, the ISS Partners, including Europe, are developing a range of health analysis and support systems for routine and emergency procedures. These will rely extensively on advanced medical information systems, computer-supported diagnostic and decision-guiding techniques, and advanced communications systems allied with novel developments such as virtual reality to guide clinical procedures and wire-less sensors and monitoring systems.

The development of these robust yet sophisticated health support systems and remotely controlled clinical procedures for space use could lead to improvements in health care delivery on Earth. Already, space-developed techniques for virtual reality imaging and manipulation by computers provides a valuable aid in developing pre-operational plans for complex surgical treatment and is now an indispensable aid for medical teaching. Health care support in remote regions, Earth-based exploration and major disaster-response operations will also benefit from the application of techniques originally developed for space use.

Astronaut Health

Astronauts are placed at significant risk of a diverse range of medical problems during their time in space. The most serious problems are the severe loss of bone and muscle, processes that begin immediately on exposure to microgravity and continue throughout the time in space, even with vigorous exercise regimes. Experiments aboard Mir showed that bone mass is lost from the lower spine, hips and legs at 1% per month throughout the mission.

Degradation of this level rules out extended missions until effective countermeasures are developed. Understanding these degenerative processes is therefore an active field of research, which deals primarily with the way in which gravity-induced stress and its unloading in microgravity change the biochemical environment and hence the functioning of the bone and muscle cells.

The solution is some way off, but it promises to be of considerable interest to medicine in general. For example, the treatment of bed-ridden patients and reducing the effects of age-related bone loss and muscle atrophy could benefit.

ESA astronaut Pedro Duque (bottom left) and 77-year-old John Glenn (top centre) flew together on the STS-95 Space Shuttle mission in 1998. (NASA)

Monitoring the health of astronauts has produced insights on the influence of spaceflight on human beings. Dedicated instruments validated in space are now used for medical diagnostics on Earth.

The ISS and its crew will be the subjects for continuing experiments into the processes of living and working in space. As we look to the long-term future of Mankind's exploration beyond the Earth, the emphasis will be on developing the knowledge derived from the basic research carried out on the ISS to permit advances in human support systems.

The ISS will be a testbed for activities such as developing new closed-loop life support systems, improving environmental monitoring equipment and designing living and working environments that improve crew efficiency and lower stress.

It will serve a similar role for developments aimed at significantly lowering the costs and risks of spaceflight. Systems aiming at the almost total recycling of onboard consumables will play an important role, since transporting items that are then discarded after one use is a high-cost luxury, especially on long voyages.

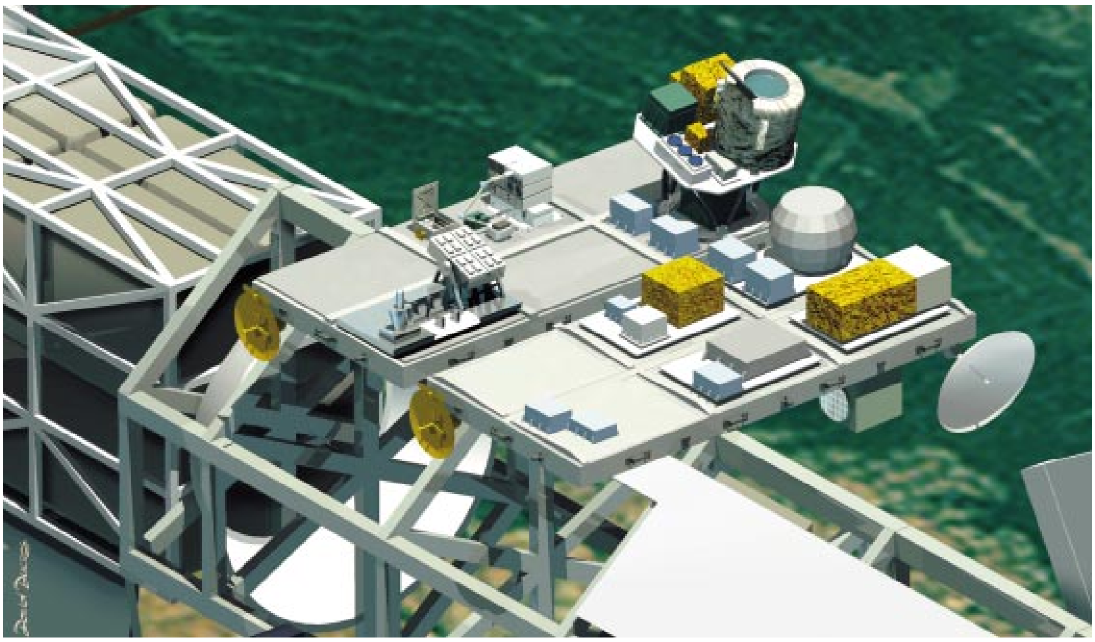
In terms of consumables, water usage is a prime candidate for conservation and recycling. Again, the knowledge derived from research along these lines will find ready application on Earth, where conservation and environment control issues are increasingly important and where water recycling is of vital concern in densely populated environments and desert regimes.

Services from Space

The Global Transmission Services equipment will broadcast data and high-accuracy time signals.

Making space 'work' for us is a primary objective of space activities; the results are an ever-present reality. We take for granted the convenience of satellite-based communications and the instant transmission of televised pictures from anywhere on Earth. Weather information and forecasting routinely use images and data acquired by sophisticated space systems. Earth observation satellites allow detailed studies in agriculture, forestry, mineral location and land use. Land, sea and atmospheric pollution is monitored on a global scale, and the biological condition of coastal and inland sea regions is examined.

In another important development, small hand-held receivers use signals from the network of Global Positioning Satellites to determine our locations at almost any position on Earth to within a few metres.



External platforms can accommodate tonnes of instrumentation. (ESA/D. Ducros)

Global Transmission Services

One of the first examples of an ISS-provided service is the Global Transmission Services (GTS) equipment, installed on the Russian Segment. Highly accurate time and data signals are transmitted, coded according to the specific requirements of the user on the ground. The Station's orbit means the signals reach each user almost anywhere on the planet several times a day for periods of 5-12 minutes.

The GTS broadcasts not only time signals but also information on the Station's position so that ground receivers can determine their time zones. The system is controlled directly from the Principal Investigator's institute in Germany.

Some expected applications are:
- accurate time receipt and automatic local time conversion for mobile users (eg wrist watches);
- car theft protection ('electronic car keys');
- coding/recoding of electronic cards (chip cards, smart cards), eg credit cards.

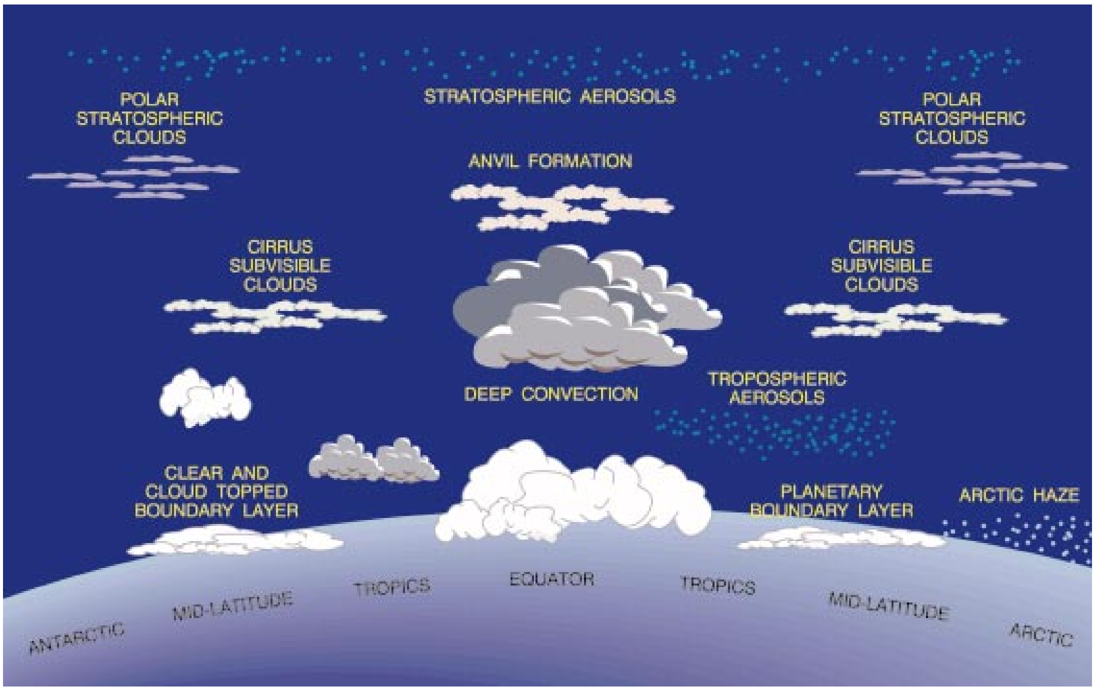
GTS services – particularly the high-accuracy time signal – are also available to users aboard the Russian Segment.

Their commercial application to all forms of navigation is already well underway. Improved, cheaper systems will become commonplace in the next decade as worldwide position locators and route finders in cars.

This direct exploitation of space for the benefit of Mankind is highly visible – and it is largely taken for granted by us all. The value of such developments is now unquestioned. Yet the cost of researching and developing each of those systems from their infancy was certainly controversial at the time. Those costs are now accepted as valid and with the growing maturity of the space segment they can be placed on a firm commercial basis.

The ISS is destined to add its own substantial contribution to making space work for us. It will contribute directly in key areas, acting primarily as a testbed for new instruments and techniques.

This unique testbed capability of the ISS derives from several large external platforms. Each is supplied with connections for power and data, and is capable of carrying tonnes of payloads. Additionally, ESA's Columbus pressurised laboratory carries external instrument accommodation, as does the Japanese Experiment Module (JEM). Pointing systems can track remote targets over part of each Station orbit. As each external instrument can be reached by robot arms directed by the crew for servicing and



Atmospheric features detectable by lidar from space, as a function of altitude and latitude.

replacement, it will be possible for researchers and industry to test a wide range of new European space systems. This can significantly reduce the risks and hence the costs of new systems destined for operations from conventional spacecraft.

Among these will be new instruments for observing the Earth's surface and atmosphere. Europe's programme aims to:

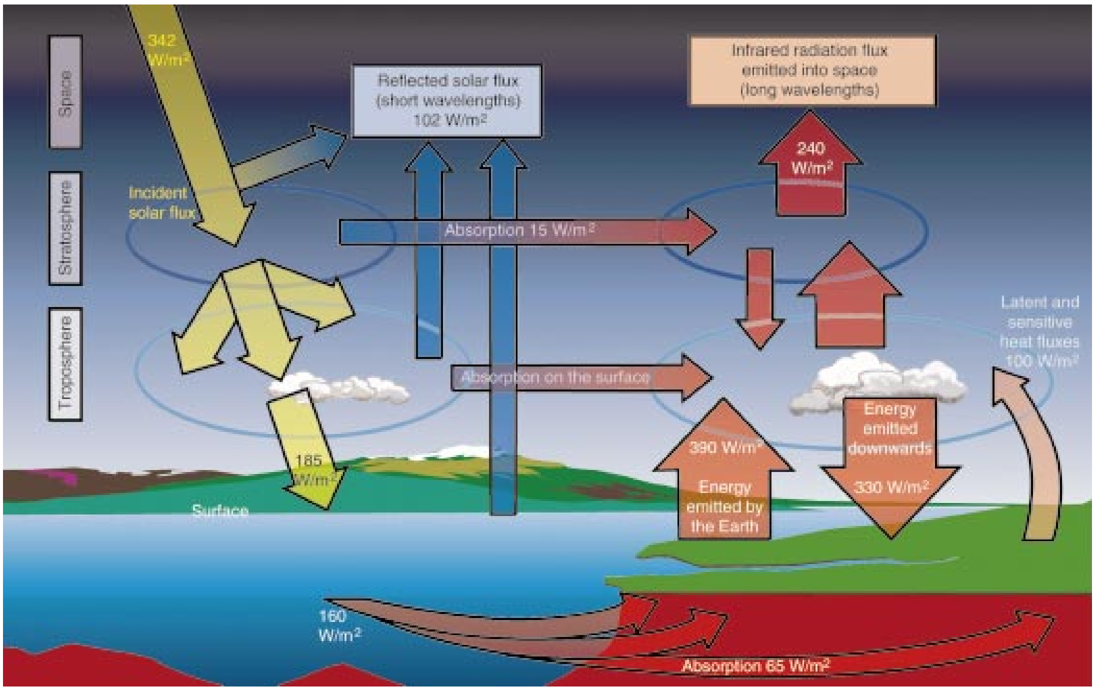
- increase our knowledge in the basic Earth sciences;
- follow and understand the evolution of changes in the Earth's global environment as it responds to the effects of Mankind's activities;
- use space-derived information on agricultural and natural resources to improve their utilisation and management.

Although the ecosystem has clearly been adjusting to change throughout Earth's history, it is the increasingly rapid rate of change over the past 100 years that appears to pose the major threat to the biosphere's continuing health. It is seriously affecting the climate. It is changing the atmosphere that we breathe, our window to the Sun's energy and our shield against the harmful solar ultraviolet radiation.

The changes to atmospheric chemistry can, through the feedback of biogenic gas emissions, lead to major climatic changes. The current rapid increase in carbon dioxide concentrations, due largely to the increasing use of fossil fuels, is the largest potential contributor to global warming. Nonetheless, other agents, such as nitrous oxide and methane, undoubtedly play a role. It is therefore important that space-based systems provide continuous long-term global and temporal monitoring of Earth's atmospheric chemistry, in order to understand the nature, extent and effects of these interlinked changes.

The ISS will contribute directly to such a programme in several ways, quite apart from testing new instruments destined to fly on dedicated satellites. Among current European proposals for Station-based studies in this field are small instruments concentrating on specific aspects of atmospheric chemistry and dynamics.

The ISS is an attractive platform for the more complex and larger instruments currently under consideration. It will allow periodic refurbishment and replacement of subsystems, such as high-power lasers. This substantially reduces the risk and allows the equipment to be updated.



The Earth's energy budget. The numbers indicate the average energy fluxes over one year on a global scale.

The ISS is also attractive for studies primarily concerned with the tropics, the powerhouse of the Earth's climate.

There is considerable interest in mounting a lidar (Atmospheric Laser Doppler Instrument: ALADIN) on ISS to measure the altitude profile of winds on a global scale, to improve the quality of operational weather forecasting and to contribute to climate studies. Lidar operates by detecting the radiation backscattered from natural aerosols at different altitudes when illuminated by a powerful laser. The aerosol drift velocity in the wind at a particular altitude slightly shifts the frequency of the laser light as it is backscattered towards the Station-based detector. Sampling that frequency shift as the Station sweeps along its orbit allows the wind velocity to be calculated.

Although the atmosphere, including the cloud cover, determines the amount and nature of the radiation that finally reaches the Earth's surface, it is the flux and spectrum of the Sun's radiation that is the source and the ultimate control of the Earth's energy supply. Small changes in the intensity and spectral content can have significant effects on Earth. Accurate long-term space monitoring of these two parameters is of obvious importance for Earth studies. For that reason, a set of European instruments will be mounted on an ESA coarse pointing system and dedicated to this purpose in the early phase of ISS operations.

Lidars

Lidars measure the radiation returned from particles in the Earth's atmosphere or from the surface when illuminated by laser. Compared with radar, lidar's shorter wavelengths provide greater detail.

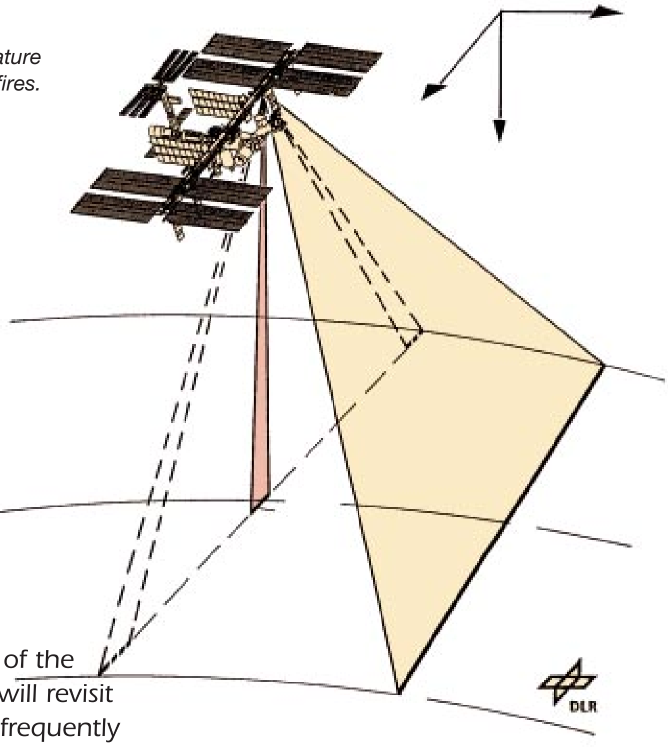
The different types of lidar measure a diverse range of parameters. Ranging and altimeter lidars provide surface topography information; for example, on ice sheet height and land altitude. Multi-frequency ranging lidars using wavelengths in the visible and near-infrared measure aerosol height distributions and cloud height.

Differential absorption and backscatter lidar measure cloud properties over wide swaths. Doppler lidars can measure 3D winds in the absence of clouds. This is of particular importance because it provides unique information for meteorological forecasting, with the potential for significant improvements in accuracy.

There are, as yet, no spaceborne lidars although some experimental instruments have flown on the Space Shuttle.

ESA plans to operate a Doppler lidar on the ISS, taking advantage of the Station's capability for supporting large and complex instruments on a long-term basis.

FOCUS will detect high-temperature terrestrial events such as vegetation fires.



The Station's orbit covers 90% of the planet's human population. It will revisit selected sites in these regions frequently and regularly, and at different local times for observations under different illumination conditions. Consequently, valuable observation programmes for Earth resources control, land use and coastal management can be developed.

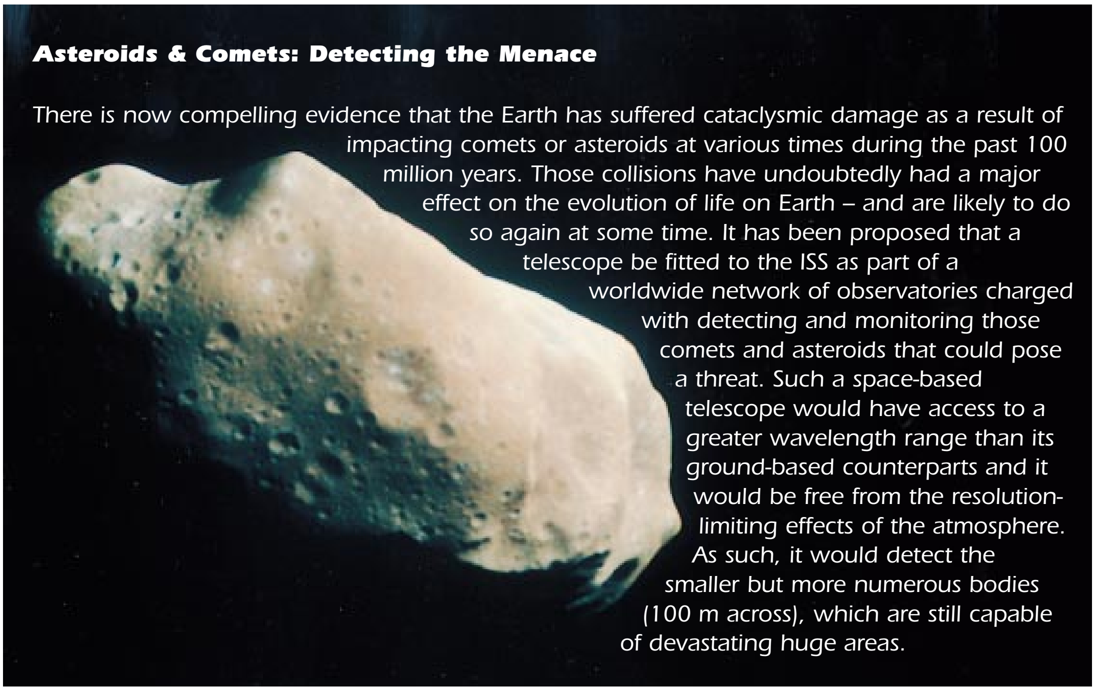
Several European proposals have been made to use the Station for these purposes, with the resulting data destined for scientific, public service and commercial users. Such activities can contribute substantially to the Global Change studies that the European Union has set out in its Fifth Framework Programme for Research and Technological Development.

Disaster prediction and warning through space observations is another example of the way that space can be made to work for us. A European instrument designed to detect and analyse high-temperature events, such as forest fires and volcanic eruptions, is planned for early flight and evaluation on the ISS (see box).

Focus on Fires

It is estimated that several million hectares of tropical and subtropical savanna land is burnt every 1-2 years. In addition, 10 million hectares of rain forest are destroyed by fire and a million hectares of Mediterranean forest and shrubland are burnt out each year. These fires add large quantities of carbon dioxide to the atmosphere, along with other greenhouse gases, soot particulates and aerosols. Their effect is to add significantly to the ongoing disturbance of the Earth's atmosphere and the resulting global-scale climatic change. Similarly, the fine particulates and gases such as sulphur dioxide ejected from violent volcanic eruptions can be distributed globally by high-speed upper atmosphere winds. For large-scale eruptions, the increased absorption and scattering of sunlight can disturb the energy balance, reflected in significant climate changes.

The total effect of these fires and volcanic eruptions on the climate, as well as their effects on the local climate and land use, has been difficult to assess so far because there has been no global-scale high-temperature event detection, monitoring and analysis system. That situation will be rectified by the FOCUS Intelligent Fire Detection Infrared System aboard the Space Station. FOCUS will determine the location and extent of fires, their nature, temperature range, and the pollutants being emitted. Such information can be accessed by ground fire management services and researchers. Similarly, volcanic eruptions can be detected and analysed. Information can be passed to agencies as eruptions progress, to aid in threat analysis and damage assessment activities on the ground, as well as providing information on the potential climatic impact.



Asteroids & Comets: Detecting the Menace

There is now compelling evidence that the Earth has suffered cataclysmic damage as a result of impacting comets or asteroids at various times during the past 100 million years. Those collisions have undoubtedly had a major effect on the evolution of life on Earth – and are likely to do so again at some time. It has been proposed that a telescope be fitted to the ISS as part of a worldwide network of observatories charged with detecting and monitoring those comets and asteroids that could pose a threat. Such a space-based telescope would have access to a greater wavelength range than its ground-based counterparts and it would be free from the resolution-limiting effects of the atmosphere. As such, it would detect the smaller but more numerous bodies (100 m across), which are still capable of devastating huge areas.

An asteroid or comet hitting the Earth would produce a disaster of cataclysmic proportions. The daily peppering by thousands of tiny meteoroids is of little consequence, but the impact of only a 60 m body would result in an explosion equivalent to a 10 Mt nuclear weapon. Such a body in 1908 devastated 2000 km^2 of Siberian forest. Evidence is growing that larger collisions in the Earth's past have triggered large-scale and long-duration ecological disasters.

The total number of these large asteroids and comets is unknown. There are estimated to be about 2000 asteroids larger than 1 km in orbits crossing that of the Earth – but only 7% have so far been detected.

Recognising the seriousness of this potential threat, the Council of Europe has urged member states and ESA to participate in the international programme to detect and establish an inventory of these larger objects and accurately determine their orbits.

It is proposed that the Space Station should carry a telescope to complement an Earth-based network. It could offer significantly improved sensitivity over ground-based instruments across a wider wavelength range because of the absence of atmospheric absorption and distortion. It would extend observations in the Southern Hemisphere, and it would cover objects, especially comets, closer in to the Sun.

ESA is considering a telescope to detect 100 m asteroids, accurately determine their orbits and then routinely monitor those orbits to check on perturbations. It would also contribute to studies of their physical nature. Searches for comets and the determination of their orbital characteristics would also be carried out as part of this important programme.

Researching and Improving Industrial Processes

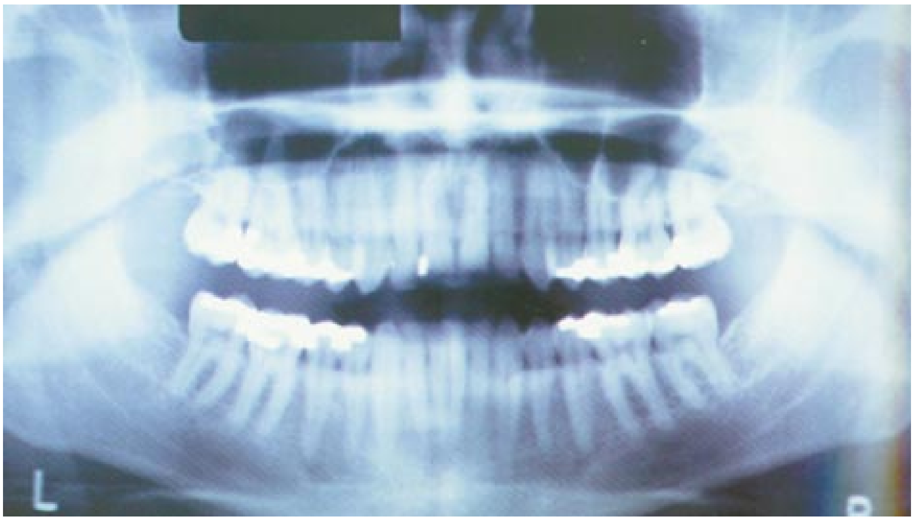
The space environment has already been extensively exploited, mostly using the microgravity conditions and, to a lesser extent, the near-Earth radiation environment. There is a highly active and valuable programme of research underway in Europe using gravity as an experimental variable. In combustion research, the removal of gravity-controlled effects on gas flow in the combustion zone allows the more fundamental diffusion-driven processes to be analysed. Likewise, the behaviour of liquid at the interface of a crystallising semiconductor is more readily investigated and correlated with final crystal quality. In both cases, the absence of gravitational effects means that temperature differences (and thus density differences) in a fluid do not produce convection, buoyancy or sedimentation. The physical picture is simplified and underlying processes can be more readily observed and analysed. The result has been major advances in our understanding of solidification and crystallisation processes in metals, alloys and semiconductors.

The motivation for such studies often begins with a purely scientific interest to question, observe and understand. But, as the short history of the development of semiconductors clearly illustrates, the answers to purely scientific questioning can quickly be taken up and applied to practical problems in device development and, from time to time, in the discovery and introduction of new devices with a major industrial impact.

Current European research in materials science in space is therefore set within an overall framework in which improvements to related industrial processes are a natural progression and are actively encouraged and supported by ESA's microgravity applications and technology programmes.

The changes in fluid behaviour in space lie at the heart of the studies in materials science, combustion and many aspects of space biology and life sciences. Using microgravity to simplify experimental conditions, the fundamental processes in fluids of many types can be more readily explored. By improving the basis for predicting and controlling the behaviour of fluids, we open up possibilities for improving a whole range of industrial processes, including the efficiency of power plants, recovery processes, and food and pharmaceuticals production. Hence a significant programme of fluid physics research forms part of ESA's microgravity activities and will expand as the facilities on the Space Station become available.

With the advent of full ISS operations, European research teams will have access to unprecedented opportunities and research facilities well beyond anything available before. ESA is providing specific materials and fluid science research facilities for the Station to satisfy many of the requirements of European experimenters. The other Partners are making similar provisions for their scientists. Since cooperation between the Partners has limited the duplication between facilities, scientists can access an extremely wide range of experiment



CdTe-based X-ray and gamma-ray detectors have high potential in real time dental imaging or mammography, including 3-D tomography. This promises faster and more reliable medical diagnosis, while exposing the patient to lower radiation doses.

equipment under cooperative agreements.

In addition, the Space Station will allow long-duration experiments to be conducted, extending the range of potential activities. Repetition will ensure data validity, an important feature unavailable on short-duration flights.

The current ESA materials and fluid sciences microgravity research programme, together with the programme planned for the Space Station, deliberately focuses on carefully selected topics that combine significant scientific interest with the potential for improving industrial processes.

Materials production in industry inevitably includes steps that are strongly influenced by gravity-driven processes. The opportunity to investigate these steps under microgravity will help to develop a more fundamental understanding of the production process and hence improve product quality and yield, and, in some cases, lead to the introduction of new products. For example, the use of electromagnetic fields for convective flow suppression, stirring and shape control is an important and well-established method for improving the industrial processing and control of growth from conductive melts. This has applications in metals casting and semiconductor crystal growth. Optimisation of process conditions in each case by numerical modelling is currently constrained by the difficulty of simulating the heat and mass transport under turbulent conditions. Experiments using magnetic fields on melts in microgravity, under well defined conditions, will provide a clearer insight into the basic processes and help to develop more realistic models of the heat and species transport.

High-Performance Alloys

New materials for the automotive and aircraft industries are intended to provide substantial weight-saving, yielding higher efficiency and lower fuel costs. However, these high-strength material components must also be produced at low cost by precision casting – not by expensive machining. Advanced computational methods and melt-flow control are used in casting to provide the necessary casting quality and precision. Microgravity studies of the molten alloys provide insights into the detailed processes occurring in solidification and aid in the definition of improved casting processes in industry. Computational modelling of the processing is also greatly improved in accuracy by the precision data from microgravity experiments on the thermophysical properties of the molten alloys. The lack of convection and of the need for containers in microgravity leads to unprecedented accuracy in the measurement of these fundamental and vital data. In a closely related European Union (Brite)-funded programme to improve the in-situ processing of aluminium matrix composites (initiated by Intospace), ESA has assisted by supporting microgravity experiments of the type outlined above.

The application potential of CdTe has not been exploited because of the difficulty in growing sufficiently large crystals of the required quality.

Recent results of microgravity experiments have demonstrated that new techniques can be employed to grow good-quality crystals.

Through similar carefully designed experiments, it has also been possible to gain new insight into the physical phenomena occurring at the growth interface in metallic materials and to understand better the processes by which the different phases in immiscible metallic alloys separate and ripen, an understanding that has led to its application in a current production process. Future research will extend these studies.

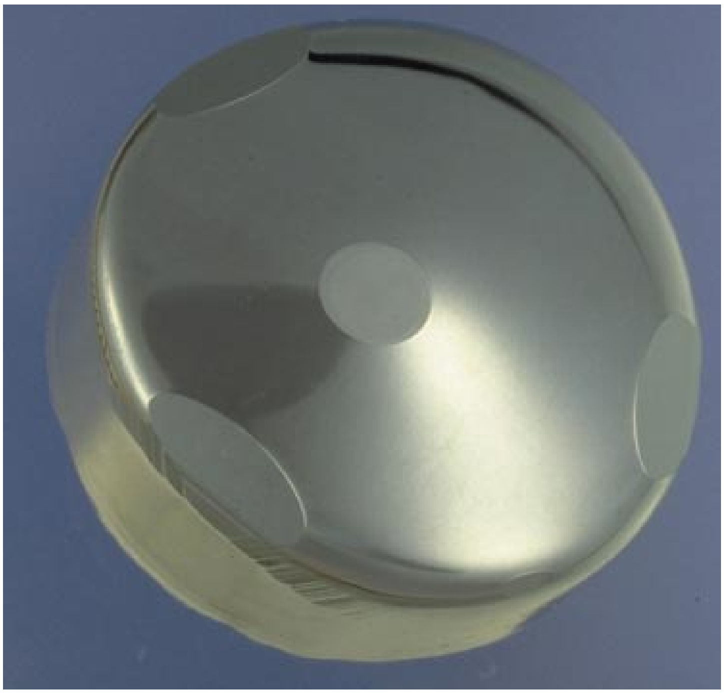
Other topics include the examination of factors controlling defect generation in the growth from the melt of commercially important materials, such as cadmium telluride and gallium arsenide. The transport mechanisms operating during the vapour growth of semiconductor crystals and epitaxial layers, used in electronic device production, are also affected by gravity. Their influence on the creation of defects that can limit device performance is another issue to be addressed by microgravity experimentation.

Despite its fundamental importance in the basic process of materials production, the understanding of how the growth of crystals and micro-crystals begins by nucleation and then progresses is still rudimentary, especially in the case of multi-component commercial materials. The lack of knowledge of the basic thermophysical properties, such as density, viscosity, diffusivity, thermal conductivity and specific heat, which are needed to develop theories of nucleation, remains a major difficulty. Accurate thermo-physical data are also vital for numerical modelling of industrial processes in casting and crystal growth. The current figures for the viscosity of molten pure iron and aluminium, for example, are known only within 50% and 100%, respectively. This lack of reliable basic data for commercial materials, as well as those for fundamental research, is largely due to the experimental problems arising from unwanted reactions of the molten materials with container walls.

Containerless methods of holding the molten materials, using electric, electromagnetic or acoustic pressure retaining forces, can avoid this problem and are now being used in ground-based studies. Their application in microgravity conditions means that the force needed for containment is greatly reduced, thereby reducing disturbances to the melt and greatly improving the accuracy of the data. Shuttle-based experiments have

Space experiments will be instrumental in validating models and demonstrating the full potential of the vapour growth technique for detector materials.

Conventional materials often do not meet the demands of industry – better control of the formation of the microstructure is required during casting.



Cd (Te, Ga) crystal grown from vapour without wall contact (5 cm diameter).

Numerical models of industrial processes are as accurate as the thermophysical data they use. Microgravity provides unique conditions for measuring thermophysical properties with unprecedented accuracy.

already provided precision thermophysical data on highly reactive alloy melts that could not have been obtained without microgravity. These containerless facilities also lend themselves to the detailed study of undercooling of molten materials, and to the production of metastable solids whose physical properties may differ considerably from their stable counterparts. Such materials may be crystalline structures, grain refined and supersaturated alloys, disordered intermetallics and quasicrystalline phases. All provide innovative materials for engineering applications. The detailed study of the fundamentals of their formation and growth under microgravity and containerless conditions will be valuable.

The advent of a permanent in-orbit capability will enable the measurement of data from experiments with industrial materials on a routine basis.

Crystal Growth of Cadmium Telluride

X-ray detectors using cadmium telluride (CdTe) have the potential to provide dental imaging, mammography and 3D X-ray body imagery in real time, with a considerable saving in time and cost, as well as reducing the exposure of patients to harmful radiation. CdTe crystals can also be used in infrared detectors for high-resolution thermal imaging and high-rate optical telecommunications.

The commercial application of such advanced detection systems is impeded by problems in growing large CdTe crystals of the required quality. This is largely due to the defects and impurities introduced from the containers of the molten material during crystal growth. Experiments in microgravity have demonstrated that new techniques could substantially improve yield. One method would progressively detach the melt from the container during crystal growth, reducing the stress and impurities. An alternative is to grow crystals from vapour. The stress and contamination are lower, although the convection effects in the vapour during growth on Earth leads to inhomogeneity in large crystals. Microgravity experiments aim to characterise the details of the vapour transport and growth process in order to permit major advances in the optimisation of CdTe crystal production.

Microgravity research is leading to new techniques for casting car engine sliding bearings.

Bearing Alloys

Some molten metal alloys exhibit two immiscible liquid phases, producing two distinct layers because of their differing densities. This prevents the formation of a uniform distribution of particles in a matrix during the casting process. Consequently, the industrial exploitation of such alloys has been limited. In weightless conditions, the density differences would not separate the two phases and a uniform distribution in a matrix might be expected. However, space experiments revealed that separation does occur, but it is driven by surface tension gradients along the surface of the melt droplets. This also occurs on Earth, since these forces are gravity-independent, and they could also interfere with the casting process. However, if the forces on the droplets owing to gravity-dependent sedimentation are balanced by the surface tension forces, then a stable dispersion of particles in a solidifying matrix can be achieved. This concept has been tested and proved. New materials – for example, an aluminium alloy matrix with distributed lead or bismuth particles – are being developed for sliding bearings in car engines.

The study of basic fluid dynamics phenomena is greatly facilitated by the use of microgravity conditions. Without the complications of gravity-driven convection flows it becomes possible to test fundamental theories of 3D laminar, oscillatory and turbulent flow generated by various other forces. The flows and instabilities induced by surface tension or thermal radiation forces, together with diffusive instabilities, can each be studied. All are of substantial practical as well as theoretical interest.

Diffusion coefficients, measured precisely in microgravity, will be used in numerical codes to provide reliable predictions of oil reservoir capacities.

Supercritical fluids may also be better studied under these conditions. Such fluids are in a pressure and temperature regime that places them in an intermediate position between gases and liquids, where they exhibit large density, low viscosity, high compressibility and large diffusivity. They are therefore sensitive to the effects of gravity and the study of their fundamental properties and behaviour is restricted on Earth. As cryogenic gases such as oxygen and hydrogen are often stored under supercritical conditions and used in reduced gravity as propellants, information from these studies finds ready application.

The absence in microgravity of hydrostatic pressure (the result on Earth of the collective weight of each vertical element in a liquid column) further simplifies fluid physics studies. The heat and fluid transport mechanisms involved in boiling can be more deeply studied and have yielded surprising data. Continuing studies have potential value in a whole range of applications in which empiricism has so far prevailed. Interfacial phenomena, phase transitions and the flow behaviour of liquids in multiphase systems, all of which are basic to many

The reliable prediction of oil reservoir capacity and oil composition enables oil companies to optimise their exploitation techniques.

Enhancement of Oil Recovery

Understanding the complex fluid physics operating within crude oil reservoirs is a major challenge, with very important consequences for successful commercial exploitation. Rising costs are forcing oil companies to develop more accurate models for predicting oil reservoir production capabilities. These models require accurate fluid physics data, particularly diffusion coefficients. These are not available from Earth-based measurements, because gravity-induced buoyancy and convection affect the distribution of the constituents in the fluids. Consequently, ESA has helped the European oil industry to establish a programme of space experiments in order to obtain accurate diffusion coefficients for a wide range of crude oil mixtures.

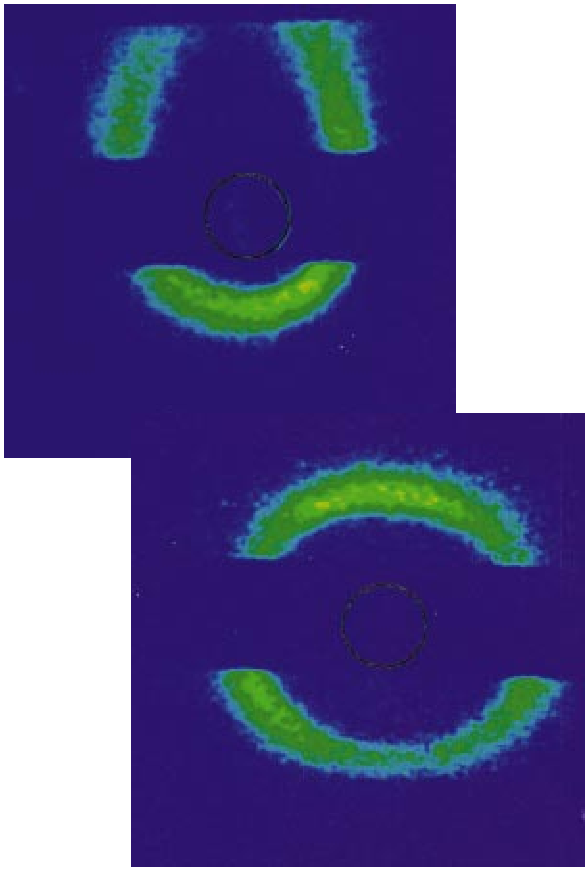
industrial processes, are open to investigation under conditions that simplify their observation and analysis.

Many industrial processes involve the use of foams and emulsions, of adsorbed layers of surface active components, and of powders. The behaviour of these materials is strongly influenced by gravity effects, which mask some of the underlying but nonetheless important physical chemistry processes. These can be explored in depth under microgravity conditions and their study forms an important part of the ESA programme.

Liquid foams are formed by gas bubbles coming together to create a liquid-gas cellular structure. They are created during many industrial processes, often as unwanted products that have to be controlled, but they are also the precursors of many solid foams, such as polyurethane. Their formation and many of their properties are controlled by surface tension, which acts at the liquid-gas interface. Under microgravity conditions it becomes possible to study the action and dynamics of the surface force-controlled processes in the creation and draining of bulk foams, providing essential basic information to help predict and understand their behaviour under industrial conditions.

Reversible adsorption plays a fundamental role in many industrial and biological processes. The familiar experience of using detergents as a surfactant in cleaning processes is only one of the many roles now played by this class of materials. Despite their increasing use to control surface properties, our understanding of the dynamics of the processes involved is insufficient to support technological needs. By performing studies in microgravity, with convection processes removed, other mechanisms can be studied and quantified.

Left: the OH concentration around a methanol droplet flame in 1 g. Right: the concentration in microgravity.



Dust particles are an inevitable product of industry and of human activity in general. We classify much of them as pollution. Yet, as powders, they are also the basis of many industries, ranging from cement to flour. Detailed understanding of the processes such as aggregation is therefore needed to improve the control and processing of these powders, and to develop scavenging techniques for their removal from machinery and air emissions.

The study of dust and powder behaviour in microgravity will aid ground-based research with long-duration experiments in sedimentation processes, allowing studies of aggregation in the absence of convection, of scavenging techniques and the study of single-grain behaviour in collision processes.

Microgravity investigations will help to unravel the complex mechanisms involved in combustion processes.

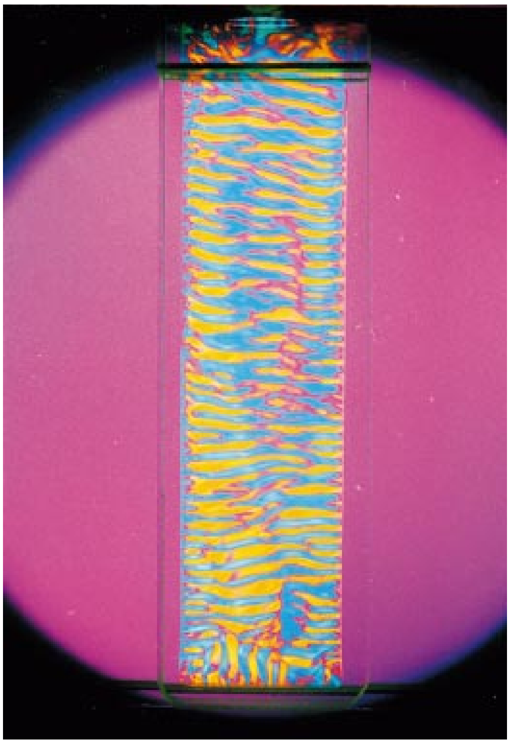
Combustion processes involve chemical reactions with large temperature and concentration gradients, leading to very strong convection-driven flows and hence to unstable burning. Controlled combustion experiments in microgravity offer the possibility for studying large steady flames. This allows the basic properties of the burning process to be studied. For example, in lean pre-mixed fuel flames, together with the influence of various fuel types and fuel injection conditions. Droplet and particle burning under high-pressure conditions – occurring in many propulsion systems – is another area in which microgravity experiments can provide valuable basic information to support modelling of industrial systems. Individual droplets can be isolated and the temperature distribution and chemical species concentration around the burning droplet analysed in a way that is impossible on Earth.

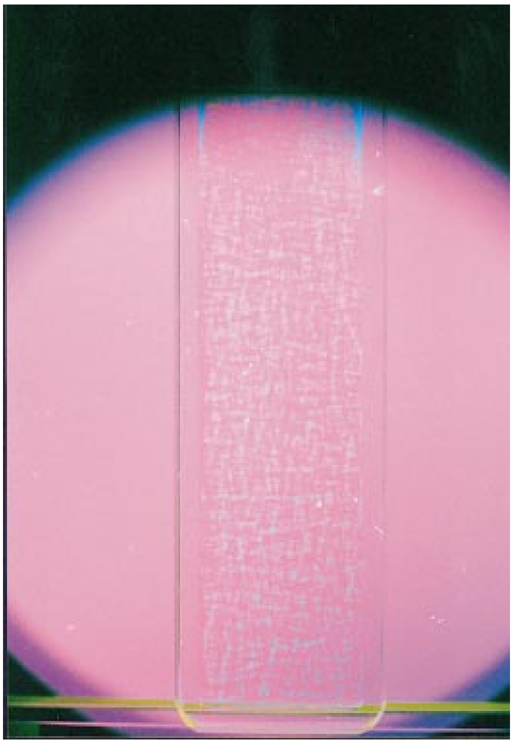
Life,Health and Welfare

Life began and developed on Earth more than 3500 million years ago, with gravity as an ever-present influence. As gravity causes sedimentation, buoyancy and convection in fluids, gives rise to hydrostatic pressure in liquids, and modifies the behaviour of liquid films on surfaces, it is not surprising that all life has developed with some gravity-sensitive processes and systems. After all, living systems are principally composed of liquids and use surfaces to isolate their different constituents as well as to facilitate and control the myriad reactions that support the process we call life.

By manipulating gravity in space experiments it becomes possible to probe these fundamental processes down to the cellular level. Removing the effect of gravity almost entirely by experimenting in microgravity, we can observe the resulting changed cell activity and function. Other gravitational levels can then be applied by centrifuge to follow the process of change.

Experimental data obtained in microgravity and hypergravity studies indicate a change in cell functions related to the gravity level. The underlying fundamental mechanisms responsible for the sensitivity of living systems to gravity remain, however, to be fully understood.



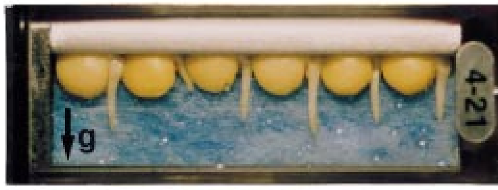


The self-organisation of microtubules in solution in 1 g (left), compared with almost no self-organisation in microgravity (right). Microtubules are the main component of the skeleton of cells. The experiment was flown on a Maxus suborbital rocket. (Courtesy of James Tabony)

Gravity and Living Organisms

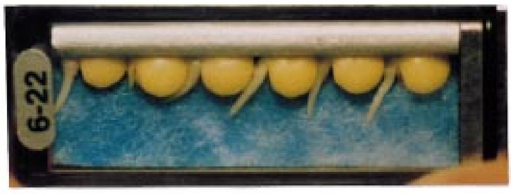
Gravity is a fundamental force, with a marked influence on all life on Earth. By using the weightless conditions in space, life scientists and biomedical researchers can observe the functional changes in cells, plants, animals and humans when the effect of gravity is removed. This can reveal the working of underlying processes which on Earth are often confused by gravity, allowing greater insight and providing answers to fundamental questions of the basic biology of these different systems. Earlier beliefs that gravity had little effect on cells other than on specialised gravi-sensing cells, such as those in plant root tips, have been confounded. Space experiments have clearly shown that when gravity is 'removed' there is a very significant effect on basic cellular processes. In plants, the equal partitioning of the genetic material at cell division is disturbed and chromosomal abnormalities are introduced, implying that plant cell proliferation requires positional cues from gravity. Other effects on plant and animal cells include changes in proliferation rates, energy metabolism, cell membrane composition and function, cell and tissue differentiation, and the rate of cell ageing. Evidently, the cellular machinery, which has evolved in a world permeated by gravity, is sensitive to the subtle modifications in its mechanical and biochemical micro-environment when gravity is 'removed'. Determining what those modifications are and how they operate will give researchers a greater insight into that cellular machinery and its functioning.

1g (25 h)



1g (25 h)

μg (25 h)

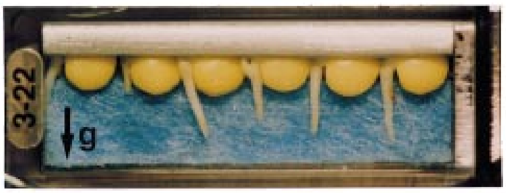


μg (25 h)

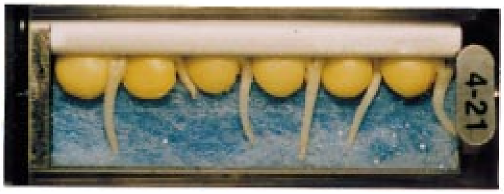
Such experiments have already been carried out and indicate that some aspects of cellular activity do depend on gravity and are disturbed under microgravity conditions. In fact, it appears likely that the effects of a changed gravitational environment are detectable even down to the macromolecular level. Individual human, animal and plant cells in microgravity have exhibited alterations to the basic cellular processes such as signal transduction, energy metabolism, nuclear division, membrane function and proliferation rates. However, there is considerable debate as to what extent these changes result from a direct perception of gravity through its effect on structures within the cell, or from an indirect perception through changes to the cell's physical and chemical environment.

In view of the fundamental importance of these changes and the insight they could provide into the cell mechanisms upon which all life depend, it is now essential to carry out a programme of carefully designed space experiments on a routine basis to establish firmly what processes are at work. ESA's Biolab facility aboard the Columbus laboratory will at last make that available.

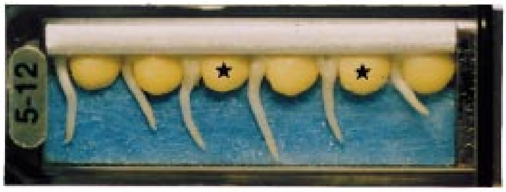
There is no question that direct perception of gravity at the cellular level occurs in those specialised cells and unicellular organisms that use gravity for orientation and movement. For example, gravity-sensitive cells in higher plants are continuously stimulated and control the direction of growth via gravity-dependent mechanisms such as the sedimentation of high-density particles within the cell. The cells at the end of root tips sense the gravity vector by this means and guide



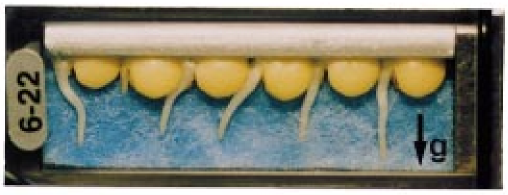
1g (4 h)



µg (4 h)



µg (4 h)



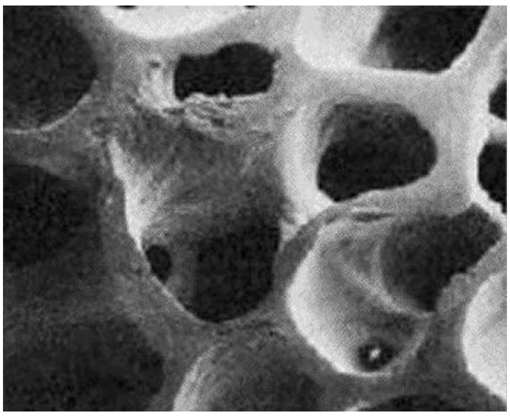
1g (4 h)

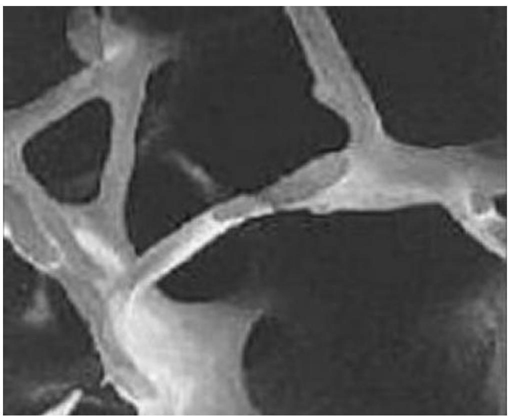
The cells on root tips guide downward growth by sensing the gravity vector. Shown are roots grown during the International Microgravity Lab-2 Spacelab mission in 1994. Top row: 25 h of growth in 1 g, followed by 4 h in 1 g. In 1 g, roots are straight and unidirectional with respect to the gravity vector. Second row: 25 h in 1 g, then 4 h in µg. 4 h of growth in microgravity already leads to loss of directionality. Third row: 25 h in µg, then 4 h in µg. Growth in full microgravity conditions shows full loss of directionality. Bottom row: 4 h of growth in 1 g after 25 h in microgravity shows re-establishment of directionality. (Courtesy Dominique Duis-Ecole & Gerald Perbal)

the root growth in a general downward direction. The value of space experiments on this class of cell lies in exploring the detailed physical and biochemical processes at work in graviperception and response.

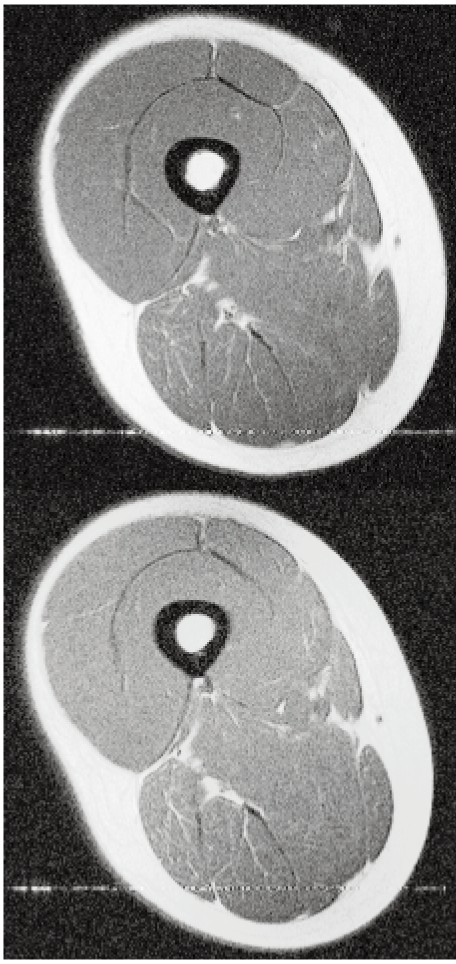
It is still unknown whether changes observed in individual human cells cultured under microgravity could manifest themselves as discernible physiological changes in the whole body. On the other hand, when searching for the origins of the many reactions of the human body to weightless conditions, it is generally necessary to consider processes occurring at the tissue, cellular and molecular levels. This is especially true in the case of the bone mass loss process, the most notable and potentially damaging of these physiological changes, whose origin lies in a changed bone cell environment and metabolism.

When astronauts enter space, there is an immediate and acute loss of gravitational loading on both bone and muscle. The bones and muscles are used in a quite different way to that on Earth, since it is no longer necessary to work against gravity to support an upright posture and walking ceases to be a natural mode of movement. In the case of bones, the response is a rapid onset of mass loss, especially in the load-bearing bones, together with an elevation of calcium





Normal trabecular bone (left) and osteoporotic bone (right). Osteoporosis affects millions of older people worldwide. Studies of the accelerated bone mass loss in space can help the search for countermeasures to the crippling disease on Earth.



Cross-section of human thighs showing significant muscle loss after 17 days of spaceflight (STS-78 Spacelab mission). Top: pre-flight; bottom: post-flight. (Courtesy P. Tesch & A. Leblanc.)

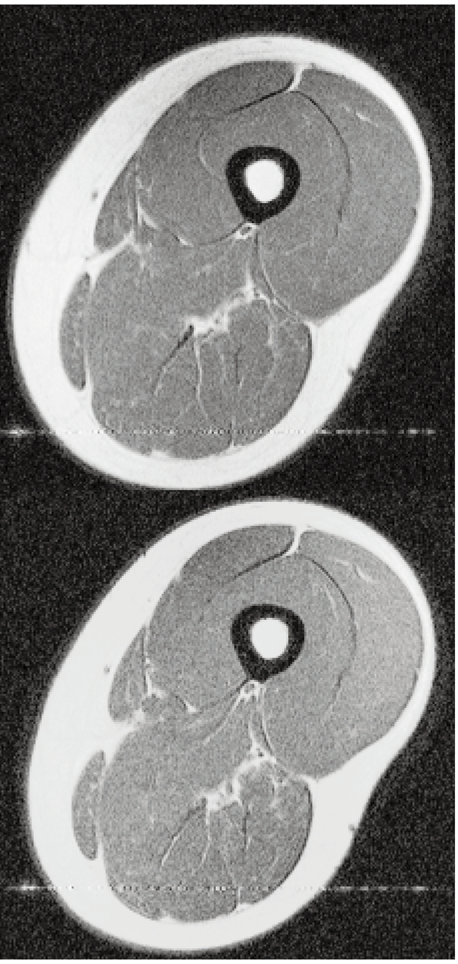
levels in the blood, with potentially damaging effects in terms of kidney stones and calcification of soft tissues in the longer-term. The bone loss continues unabated throughout the time in orbit, at a rate of about 1% per month. This sets a limit to the time that crews can safely remain in orbit, if they are to avoid serious risk of bone fractures on return to Earth.

The mechanisms driving this bone loss and those causing the accompanying muscle atrophy and changes are unknown. Bone is a dynamic equilibrium between bone cell growth and destruction. This equilibrium can be disturbed by factors such as hormones and vitamins in the blood, as well as the mechanical stressing of the bone. Microgravity conditions may alter all of these but it is likely that the basic process follows from the unloading and reduced stressing of bones and muscles, which modifies the stretch-activated chemistry at the cellular level. Exercise regimes have had little success in retarding the bone loss and muscle atrophy. It is more likely that a solution will be sought through modifying the biochemistry at the cellular level.

Muscle atrophy and loss of bone mass afflict the elderly on Earth, and especially post-menopausal women in the case of bone loss. In seeking a solution to the problems facing astronauts, it is quite possible that the knowledge may contribute to finding ways to ease those problems on Earth.

Microgravity is a new non-invasive tool to investigate cellular functions. It provides new insight into how cells perceive signals and react to them. This is essential for the better understanding of biological and physiological processes, with potential applications in molecular medicine, such as wound and tissue repair.

Other changes in the human body are observed when microgravity conditions are encountered. Again, their investigation is leading to new insights into fundamental physiological processes, raise important questions and promote understanding of the body's functioning at a basic level. For example, the rapid upward displacement of body fluids that follows once the downward pull of gravity disappears automatically triggers responses in heart and kidney functions. There is an increase in fluid and electrolyte excretion by the kidneys and an increase in blood being pumped by the heart, together with a redistribution and elimination of plasma. Careful investigation of these and related processes provides scientists with a valuable tool to extend understanding of basic body fluid regulation processes involving the kidneys, the glandular system and the heart. The results are valuable not only for developing space



countermeasures, but also for understanding medical aspects such as the mechanisms of various heart and kidney diseases.

The human respiratory system should also be sensitive to gravity. Indeed, weightlessness leads to changes in the chest wall mechanics, the relative displacement of the rib cage and the abdominal compartments.

It was also expected that weightlessness would result in a reduction of the observed inhomogeneities in blood and air flows between the upper and lower parts of the lung. However, the inhomogeneity was also found in microgravity. In other words, microgravity experiments had proved that the origin lies in the lung's intrinsic structure and not in the influence of gravity-generated forces, as the textbooks had always maintained. Details of the lung ventilation and blood perfusion patterns remain to be studied, taking advantage of the lack of gravity effects to clarify the basic processes. Similarly, the mechanics of breathing and the neurophysiological adaptation of the respiratory system as it encounters low gravity and radically changed biomechanical conditions need investigating. The possible relationship of these changes with breathing and the sleep disturbance experienced by crews requires analysis.

There is much to be studied and much that will be of value to Earth-based research in pulmonary function and its clinical application.

The profound changes induced in the human body as a whole upon entering a microgravity environment include disorientation, which occurs within minutes and which is usually accompanied by nausea lasting for several days until adaptation occurs. The cause lies in the

Space Aged

Some of the physiological changes observed in astronauts in space bear some similarities to those that develop as a result of the normal ageing process on Earth. The difference is that the changes in space begin to occur rapidly upon entering weightlessness and can therefore, to some degree, provide an accelerated view of certain ageing symptoms. The most notable changes are the sudden onset of bone loss and muscle atrophy, partly due to deconditioning and disuse but also probably involving more fundamental changes at a cellular level. Similarly, there is a deconditioning of the cardio-vascular system and an apparent depression of the immune response system. There is also an incidence of balance disorder in the first few days in space. By studying the causes of these degenerations and disorders it will be possible to reveal the fundamental processes that are at work. Those results will be used to develop drugs and countermeasures to reduce the severity of these effects for future astronauts. They will also be available to help understand those ageing changes that give rise to similar symptoms on Earth.

ESA's rotating chair centrifuge flew on the Neurolab Spacelab mission in April 1998. The off-axis rotator spun to stimulate the inner ear.

disturbance to the acceleration-sensing system of the inner ear, a system that registers the force of gravity and contributes to defining posture and balance on Earth. There are also visual-orientation illusions and feelings of self-inversion, which also owe their origin to the loss of appropriate signals from the mechanical receptors in the muscles, tendons and joints, and from the skin's pressure sensors, especially on the feet.

The progressive adaptation of astronauts to this environment indicates that the nervous system can compensate effectively for the loss of gravitational stimuli. It does so by neuronal plasticity, in which the nerve cells react to new conditions by changing cellular dimensions and making new connections or adapting earlier ones. In other words, the phenomenon of neuronal plasticity amounts to a learning process. The question has been to what extent the peripheral neural system involving gravity-sensing mechanisms is included in this learning process, as distinct from the central neural system.

Space experiments have shown that, in the case of the inner ear, the adaptation to microgravity occurs largely by a progressive increase in the number of communication sites, which lie between the gravity sensor cells, and the nerve fibres ending on them. This observation of rapid adaptation, starting within hours of exposure to a new environment, confirms that these peripheral sensory elements do indeed learn and respond rapidly to the changed environment. Such information has potential value in the treatment of balance disorders on Earth, a problem that affects millions of people, as well as being of direct interest in improving the welfare of astronauts.

Neuronal plasticity is also involved in the adaptation to changes in the body's daily rhythm imposed by orbital flight. The body temperature, heart rate and activity level, for example, show a natural circadian rhythm, which is synchronised with Earth's 24-hour day. Space experiments have shown that weightlessness affects these rhythms, but the mechanism is unknown.

New experiments are examining the effects of microgravity on nerve cells in the brain of animals, using molecular markers of early neuronal plasticity to study the region of the brain where modification and adaptation are occurring.

These investigations into circadian rhythms and their basic mechanisms are of potential value to researchers seeking the causes of jet lag, insomnia and disorders such as winter depression.

Radical changes in the structure and connections of the nerve cells occur during the early development of the nervous system. As those changes are regulated by mechanical and biochemical factors, it is thought that gravity may play an important role in stimulating the proper development of the nervous system on Earth. For example, animals deprived of the opportunity to walk during their first weeks after birth never learn to walk properly. Studying how that development proceeds in animals under weightlessness will help to define the respective roles of genetic determination and environmental experience.

Understanding the nature of these critical periods of neural development has important implications for paediatrics. It could also help in the treatment of those suffering from neuromuscular diseases.

The subjects for all of these studies into human functioning in microgravity are the astronauts themselves. Therein lies the problem that has dogged space physiology over the past decade. Not only have the flights been limited, but so have the number of subjects. How much of what is observed is due to individual differences? How much is due to the difficulty of providing controls in an environment where the subjects are few and have differing regimens?

The facilities, too, have been limited. The Space Station will not solve all of these problems but it will greatly enlarge the pool of astronauts, provide better opportunities to control the regimen of subjects over time, offer repeated testing procedures, and enormously improve the test facilities available for life sciences investigations. These improvements will provide for better and more extensive life science research in the future. It will lead to improvements in the health and welfare of future astronauts and make extended flights safer and easier. Beyond that, however, it will continue to provide and extend the valuable information contributed to medical studies in general, to the ultimate benefit of our health and welfare on Earth.

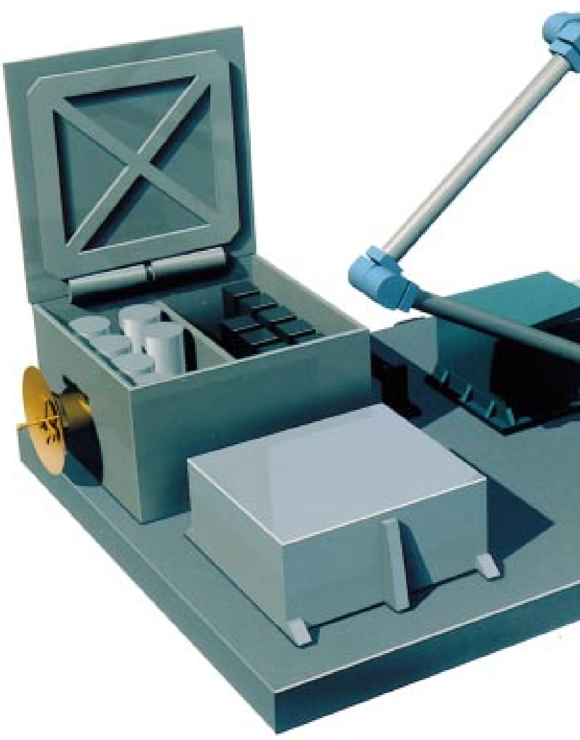
Space Commerce and Applications

Space commerce is a feature of everyday life. Indeed, the operation of the global economy is its manifestation: the rapid development and ultimate commercialisation of global space communication systems have permitted information to flow readily and cheaply across the Earth.

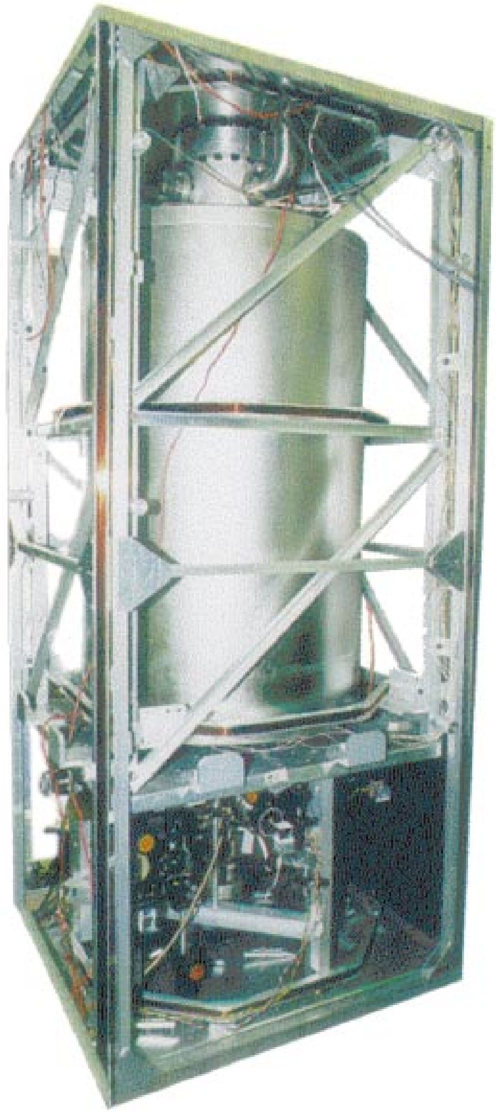
In parallel developments we have seen the expansion of Earth-observing space systems, providing information on an increasingly commercial basis to government and commercial users, and of space-based aids to global navigation and position location. Developments in the commerce of space probably depend on incremental improvements to the above systems, aimed at increasing their capabilities while reducing their construction and operation costs, to the benefit of an increasing number of customers.

Space commerce will also gain from improvements and cost reductions in launch vehicles, in spacecraft systems and in their operating and control systems. The Space Station has a role to play in that development process, since it is a large space-based test facility offering manned intervention and frequent change-out of system components. Consequently, new elements ultimately destined for large and expensive communications or observation spacecraft can be tested on-orbit, reducing the risks and enabling improved designs to be progressively developed before being implemented in costly commercial spacecraft.

Partly with that in mind, ESA is providing the Technology Exposure Facility (TEF) for external accommodation of test modules. TEF's early use is foreseen to test a high-temperature superconductor system destined for use in satellite communications to provide power saving and enhanced performance. TEF will also test the performance of electric propulsion systems that are likely to find application on communications spacecraft for orbital transfer manoeuvres, station-keeping, attitude control and drag compensation. The introduction of such systems is expected to lead to substantial launch mass reductions, and hence cost savings, by avoiding the need for



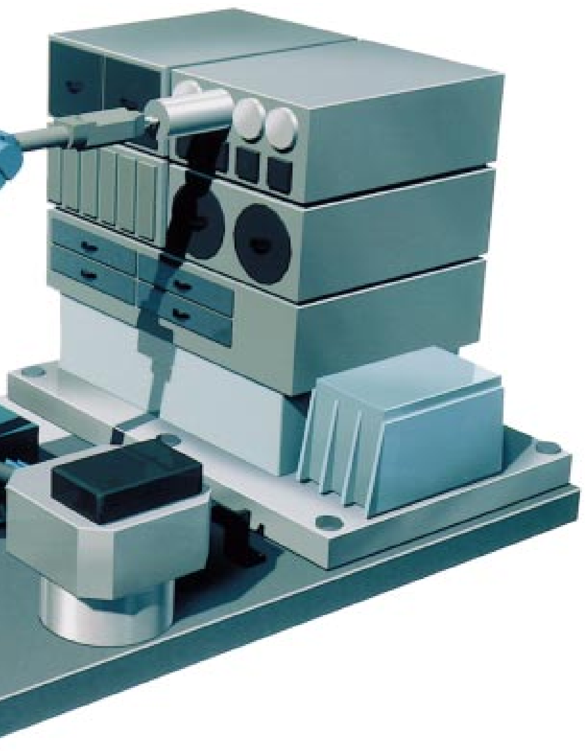
Artist's impression of a concept for ESA's Technology Exposure Facility.



This atomic fountain clock, operating in the Observatoire de Paris since 1995, is the world's most accurate clock.

chemical propellants. In the longer term, electric propulsion will also find application in interplanetary missions.

Other applications may include the space testing of life support systems for future long-duration missions and the testing of advanced thermal control systems to enable higher power operations on communications and Earth observation spacecraft. The space radiation environment will be used to expose and monitor the behaviour of a variety of materials that may find future application in space. The Station's local external environment will also be monitored.



Very high-precision time reference systems, coupled with time synchronisation facilities, form the foundation of a host of applications. Major improvements in time measurement and synchronisation can therefore translate into important new developments in diverse fields. For this reason the European project to place the Atomic Clock Ensemble in Space (ACES) on the ISS has excited considerable interest.

Cold atomic clocks operate by locking a microwave oscillator onto the resonance frequency of an ensemble of caesium atoms held at extremely low temperatures. The longer the time for interaction between the microwave field and individual atoms, the higher will be the accuracy of the resulting time measurement. Microgravity conditions will

Time and Space

Gravitation is a space-time property according to General Relativity. Its geometry is defined by the matter and the radiation it contains. Hence, a massive body such as the Sun modifies the local space geometry by its presence, leading to a bending of light as it passes near the body, and to retardation and frequency shift of light emitted. Measurement of these effects depends upon the ultra-precise measurement of frequency and time, which in turn depends upon the cooled atomic clock, currently the world's most accurate. Its operation depends upon the cooling of caesium atoms to a temperature of about 1μK by a laser system, which slows down their thermal velocity. Then a microwave frequency is locked into the extremely narrow resonance frequency of the cold caesium atoms. The final accuracy of this system depends upon the length of time that a caesium atom can interact with the microwave field. On Earth, gravity causes the caesium atoms to increase their speed rapidly when the lasers are switched off for signal interrogation. By going to microgravity in space, it is expected that the interaction time will increase by a factor 10 and the final accuracy in time measurement will be one to two orders of magnitude better than achievable by the best Earth-based clocks. The French ACES payload for the Space Station will combine such a clock with reference clocks and microwave and laser links to ground to provide a global time scale of unprecedented accuracy. In addition to its role in basic gravitation experiments, it will also provide the time correlation for receiving stations in very long baseline radio interferometry observations to a new accuracy, thereby improving the resolution of remote stellar objects. It will also lay the foundation for a new level of precision in global navigation systems, and it will allow geodesy measurements to millimetre precision.

substantially extend the residence time of the atoms in the microwave field, improving the accuracy and stability of the cold atomic clock by about an order of magnitude over its ground-based counterpart. ACES' other components comprise other types of precision clocks for comparison, and microwave and laser time and frequency links to the ground to provide a worldwide precision time standard.

This Station-based ACES system will allow the comparison and synchronisation of clocks over intercontinental distances to an accuracy of 1 part in 10^{16} and allow the distribution of International Atomic Time of 100 times greater accuracy. The ACES clocks could be the heart of a new space-based Global Positioning System concept that would provide major improvements in the precision of position, distance, and velocity measurements, thereby extending the commercial use of this system even further. Large-scale measurements of the Earth's surface could also be greatly improved in accuracy, in principle allowing crustal movements to be monitored with millimetric precision, thereby widening the scope and application of geodesic measurements.

This crystal of the membrane protein complex Photosystem I was grown in space in ESA's Advanced Protein Crystallisation Facility. 4 mm long and 1.5 mm in diameter, it yielded the best data set ever obtained.

Biotechnology is the application and commercialisation of biology. It generally involves turning molecules, cells, tissues and living organisms into marketable products with high added value by virtue of advanced science- and engineering-based techniques. It is a commerce still in infancy, but rapidly evolving. The use of the microgravity environment of space for biotechnology research and development is already underway but the Space Station will accelerate the process.

Of current activities, those relating to eventual drug development are of particular interest and involve protein crystal growth studies. An accurate knowledge of the 3D structure of proteins, of which there are about a million different types, is required in order for a full understanding of the function of each. As yet, only a few hundred protein structures have been determined, a major difficulty being the lack of large crystals of sufficient quality for X-ray analysis.

As expected, the absence of sedimentation and convection in microgravity alleviates some of the problems of getting these large protein molecules to crystallise. Several key proteins of particular interest to the pharmaceutical industry for drug development to treat disease are under study. In the USA, knowing the space-derived detailed structure of a protein that enables the spread of influenza in the body has led to the design of an inhibiting drug, with very promising results in culture and animals. With the ISS, European facilities and opportunities for protein crystal growth on a continuing basis will be greatly expanded. At the same time, the current basic research by European scientists into the detailed mechanisms that control the growth of protein crystals will be speeded up, so that commercial activities can be placed on a much firmer base.

Crystals of a biological macromolecule enable researchers to determine the structure of the macromolecule and understand its function.

Knowing the structure of a macro-molecule permits a faster selection of the appropriate drug, or the design of a new drug.

The lack of good-quality crystals precludes the precise determination of molecular structures with adequate precision.

The benefits of low gravity for growing cell cultures rest on the absence of convection and sedimentation, which for 3D cell aggregates favour the creation of a tissue-like environment.

Millions of people suffer organ or tissue loss from diseases and accidents every year. Yet the supply of tissues and organs for transplantation is severely limited by the lack of donors. Growing tissues outside of the body is one of the goals of current medical research, and microgravity has considerable potential for advancing this research and its application in biotechnology.

Previously, it proved almost impossible to grow representative tissue samples outside of the body. Gravity-driven sedimentation and convection cause cells to form 2D rather than 3D aggregates. In microgravity, this problem is absent and experiments in space bioreactors have enabled studies on how cells multiply and can interact to form skin, bone and organs. They have also allowed tumours to be grown, subsequently allowing treatments such as chemotherapy to be tested for efficacy outside of the body, as a preparation for clinical application.

Knowledge gained from space experiments on the regulation and differentiation of cell growth will also help to improve the cultivation of sensitive and highly differentiated cell strains such as those needed to produce artificial organs. Studies of the ability of cells to migrate in microgravity conditions may also be valuable in providing insight into how certain cancers spread within the body. When combined with biomedical research on Earth, including that within the European Union Fifth Framework programme, these investigations will contribute to the development of biotechnology and new ways to prevent and treat diseases.

Biological Macromolecule Crystals and Drug Development

Proteins are the working macromolecules of the cell. They provide, for example, the structural rigidity of the cell, control membrane permeability and, acting as catalysts, control an extraordinary range of chemical reactions. In so doing, they recognise and bind or interact with other biomolecules in a very specific manner, determining the biological function. In order to understand exactly how a particular protein acts in a specific cell reaction process, it is necessary to know its 3D structure and chemical constitution. That can be done using X-ray analysis, provided that large high-quality crystals of the protein can be grown. Knowledge of protein structures is also invaluable in the fight against diseases. For example, armed with a detailed knowledge of the structures of the active protein on the surface of a virus and that of the receptor protein on the surface of the cell being attacked, it is possible in principle for biochemists to design a drug that targets and interferes with that interaction process and stops the viral infection developing. Despite the obvious importance of proteins in normal cell functions and their role in diseases and disorders of the body, very few of the huge number of different proteins have been successfully crystallised and their structures determined. The problem is partly due to the gravity-induced convection and sedimentation processes at work in the solutions in which these fragile crystals are grown. Microgravity removes such disturbances and improved success in protein crystal growth has been achieved. At the same time, a research programme to study the fundamentals of the protein crystal growth process using microgravity is underway, in order to further increase the success rate and to apply the results to the ground-based processes.

Extending Frontiers

The drive to explore, to probe into the unknown, to question why, seem to be innate and unique characteristics of the human race. They lead us to try to understand more about our planet, our neighbouring worlds and the infinity stretching beyond. How are stars created and planets formed, where did life come from, how can it survive, does it exist elsewhere, are we really alone? These are questions that drive us to explore new frontiers in astrobiology, planetology and astronomy.

The Space Station will contribute to the quest by hosting a whole range of astronomical instruments designed to study a diversity of Galactic objects, for example, covering the birth, life and destruction of stars. It will carry space environment probes that can analyse cosmic dust and study the exotic components of cosmic rays. It will test new detection systems, attempting to observe the waves of gravitational energy released in cataclysmic events in our Galaxy. Microwave radiometers will take advantage of repetitive scans and coarse pointing on the ISS to determine the polarisation of the diffuse radiation permeating the Galaxy. This can provide information on the overall structures of the interstellar magnetic fields, ionised gas clouds and highly energetic electrons. At the same time, it should be possible to detect any polarisation in the cosmic microwave background radiation. This is the remnant energy from the Big Bang explosion that created our Universe. An observation of polarisation in that radiation will help to resolve uncertainties between differing cosmological models. The ACES atomic clock ensemble described in the previous chapter will enable measurements of Einstein's gravitationally-induced redshift of spectral lines to be determined with a factor of 100 improvement in accuracy. Similarly, it will improve the measurement accuracy of the bending effect of the Sun's gravitational field on light. It will also permit important checks on the stability of the fundamental 'constants' of physics, assessing possible time-dependent drifts or spatial effects.

Attempts at unifying gravity with other physical forces prompt the conclusion that the gravitational force on matter and antimatter is perhaps different at some as yet unknown level. At one extreme, it has been proposed that antimatter could be repelled by gravity. If it were, it might explain the apparent absence of antimatter on a large scale in our Universe – matter and antimatter would have separated in the early Universe.

An experiment has been proposed to take advantage of the microgravity environment and the low-temperature facilities to measure the weight of the antiproton particle. This would establish limits on any difference between the influence of gravity on normal matter (represented by the weight of the proton) and on its antimatter equivalent (the antiproton). These antimatter particles can now be created and collected in magnetic traps in large accelerators for examination elsewhere.

Exploring the Early Universe

The Universe has been continuously expanding since its creation in the Big Bang some 15 billion years ago. Cooling as it expanded led to the formation of primordial matter and ultimately to coalescence of neutral atoms into gas clouds. Within a few billion years, the first galaxies were created and major star-forming activity was underway. The details of the processes leading to this point are still to be explored and take us to the forefront of astrophysics research.

As the Universe has continued to expand, an observation towards the present outer limits of that expansion means that we are viewing the remnants of that earliest epoch. In other words, we are looking back in time to some of the earliest objects created. However, their enormous distances make them appear very faint, so that large telescopes, very long observing times and freedom from interference by the Earth's atmosphere are helpful.

The Hubble Space Telescope has provided us with a glimpse into this early Universe by observing a tiny patch of the sky (160 arc seconds square) for 10 days, as shown here.

This image contains about 2000 objects stretching back about 10 billion years. Most of these objects are galaxies, although many are different from more recent types. Hubble is continuing the detailed study of the early visible Universe but, in order to investigate the high-energy phenomena, it is necessary to generate similar images in X-rays. That is possible only by constructing an X-ray telescope large enough to collect, detect and resolve the emissions from those faint distant sources. To do that requires an X-ray telescope of up to 10 m diameter, far larger than any current telescope and beyond the launch capabilities of any single vehicle. ESA therefore proposes to exploit the Station's unique capabilities and supply vehicles to build the advanced XEUS (X-ray Evolving Universe Spectroscopy) telescope system in stages. Robotic and manned involvement are required for its construction, maintenance and resupply.

The accuracy of the Space Station experiment would be a thousand times better than that of the Earth-based version. It would therefore provide an important and precise test of the applicability of Einstein's Weak Equivalence Principle for the case of antimatter.

The ISS can also respond quickly to events such as very large solar flares and coronal mass ejections, which can directly affect Earth's climate. They can be studied in detail as they occur by the available solar observation instruments.

In many of these activities, the Space Station instruments complement those carried by dedicated satellites such as the Hubble Space Telescope. They may also be pathfinders for dedicated missions, using the Station's unique capability for human intervention during testing. The value of such intervention has been clearly demonstrated in the case of Hubble, where essential modifications to the optics and exchanging instruments have been major factors in the observatory's success. In the case of instruments on, or tethered closely to, the ISS, human intervention will normally be simpler and much less risky than with Hubble – many operations will be performed by crew-controlled external arms fitted with sophisticated manipulative 'hands'.

The Space Station's unique capability for enabling the construction of large structures in space is being amply demonstrated as the ISS itself is

progressively enlarged on-orbit. It is natural to exploit that capability as the frontiers in space science are extended and new exploration missions are planned. The trend is towards ever-larger experiment systems lying beyond the launch capacity of existing vehicles.

For example, there is a need in radio astronomy to improve resolution so that the small yet extremely powerful radio sources lying outside our own Galaxy can be clearly seen and their physics analysed. That requires an increased separation of the two telescopes forming the interferometer. Placing one telescope in space can greatly enlarge that separation, but it also requires a very large telescope there if the sensitivity for detecting distant sources is to be maintained. Current plans are for a telescope of 30 m diameter to be assembled at the ISS, tested and then released into an independent orbit for routine operations.

There is compelling evidence that cellular life forms flourished on Earth some 3500 million years ago, implying that it developed despite the extreme conditions as our planet recovered from the effects of the massive bombardment by asteroids and comets in its early history.

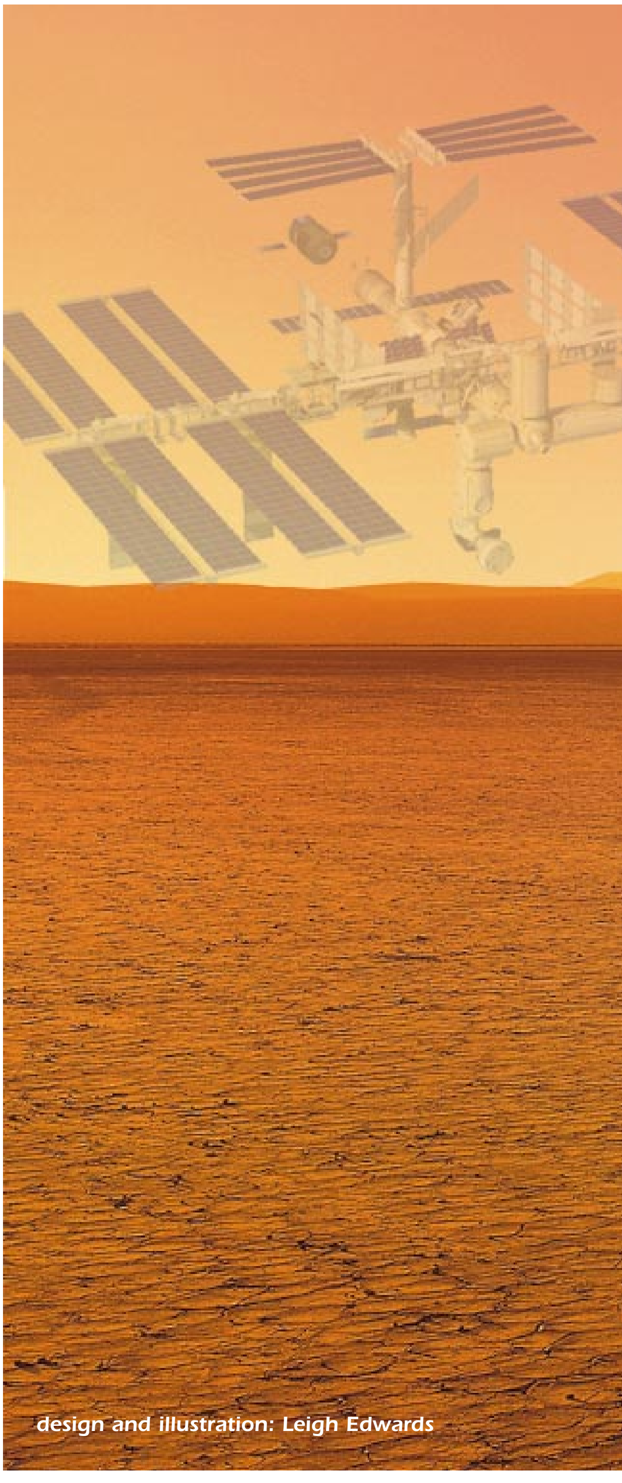
There is little doubt that, during that late bombardment, much of the life-giving water and organic matter was deposited by comets. Did they also bring with them the simple constituents of life? Can the basic building blocks of life survive the harsh environment of space? We do not yet know what level of complexity of organic chemistry and organisation can survive the journey lasting millions of years through space before arriving on some planetary body and perhaps triggering the earliest stages of what we call life.

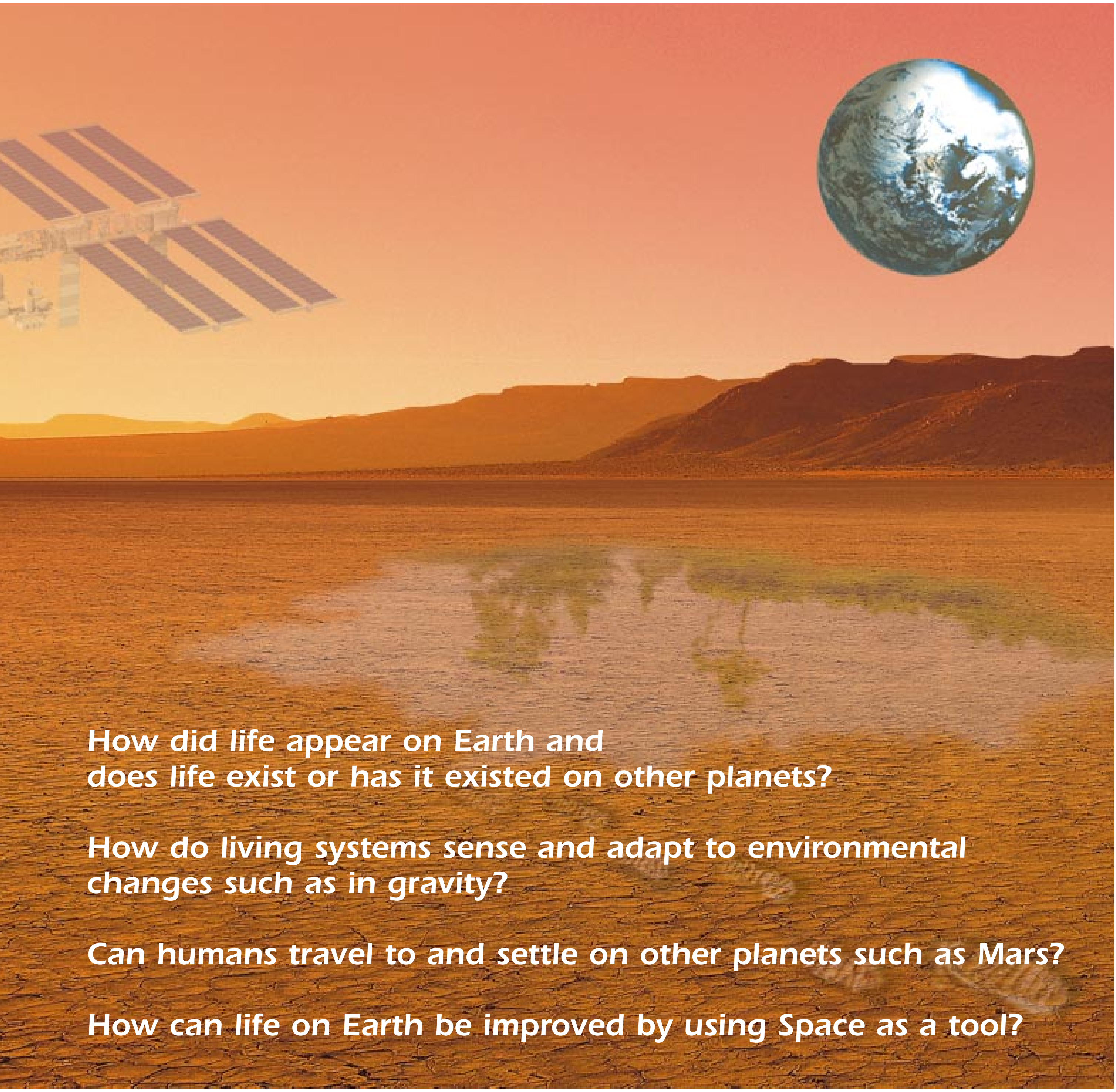
The Space Station will therefore be used to continue exobiology studies on the effects of the total space environment (radiation, microgravity, vacuum and intense cold) on simple life forms and prebiotic chemical systems.

To reach beyond that point in the search for the very earliest forms of life we need to go beyond the Earth. Those earliest records of life on Earth have been destroyed by the movements and reprocessing of the earliest land masses. There are no fossils of primitive life older than 3800 million years. To have a chance of observing the earliest life forms *we need to breach a new frontier: exploration below the surface of Mars, a planet much like Earth in its early form but free of the total transformation of its early land masses. Did life exist there? Probably, but we must go there to prove it. To do that, we need the International Space Station.*

Manned exploration of Mars and the Solar System is a long-term goal. Many challenges remain before humans can safely and sensibly travel to the planets and live and work there. The ISS will play a vital role in preparing Mankind to explore this new frontier. It will be used in engineering studies and tests of new technology, new types of system architecture and operating methods. It will support the basic and applied science that seeks to understand the influence of space on the human body, of ways to maintain the health and welfare of astronauts over extended periods in space, to develop methods exploiting the resources of planets for water and oxygen, and to recycle wastes of all types in order to reduce the dependence on supplies from Earth.

The challenges presented by this new frontier are daunting. The International Space Station provides the gateway to that new world.


design and illustration: Leigh Edwards



How did life appear on Earth and does life exist or has it existed on other planets?

How do living systems sense and adapt to environmental changes such as in gravity?

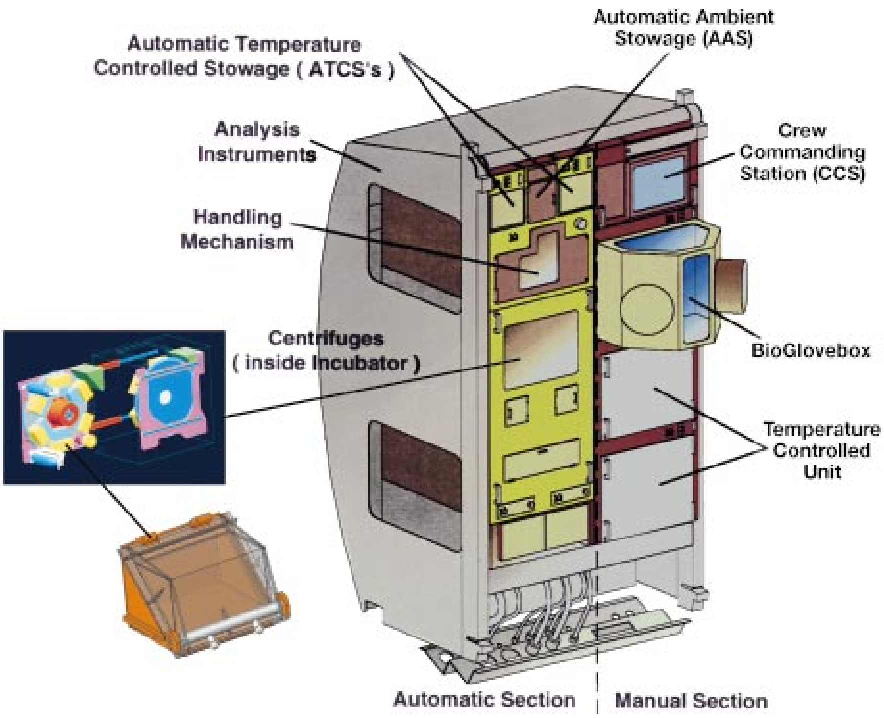
Can humans travel to and settle on other planets such as Mars?

How can life on Earth be improved by using Space as a tool?

Questions: A European Research Agenda

The ISS utilisation resources (power, data, crew time and up/down mass) available to Europe are a modest (8.3%) fraction of the total available to the other non-Russian Partners. In addition, the resources available to users during the assembly phase are limited because of the allocation of resources to the assembly work itself. For these reasons, European utilisation plans must focus on extracting the maximum benefit from the investments made in ISS facilities. Aggressively pursuing cooperative research with other Partners is also necessary, allowing European researchers access to research opportunities not necessarily available to them otherwise.

Biolab will support biological research aboard the Space Station. (ESA/D. Ducros)



Much of the responsibility for focusing the research and guiding the technological exploitation of the ISS within ESA devolves upon the various scientific and technological advisory groups and the Space Station User Panel.

These various groups have reviewed on-going space research in their areas of specialisation and analysed the response to calls for experiment proposals in their respective areas. Their recommendations have guided ESA in its development of facilities for ISS utilisation and in planning an overall research and technology strategy. Behind that strategy lie basic questions that need answering and for which the ISS and its facilities are judged as the appropriate means of addressing them. The following summary indicates the line of questioning that has laid the foundation for Europe's near-term use of the International Space Station.

Space Biology and Exobiology

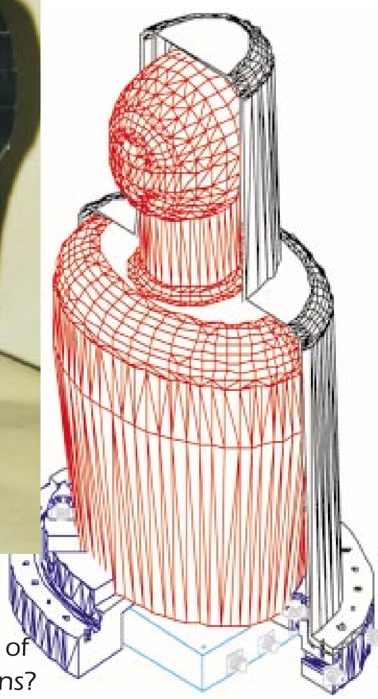
Space biology will continue to concentrate on fundamental studies relevant to on-going ground-based research, using the elimination of gravity-driven effects to expose underlying processes, particularly at the cellular level. Some of the general questions to be addressed are:

- How do living systems sense and respond to gravity at the molecular, genetic and cellular levels? How does microgravity influence the regulatory mechanisms and signal transduction processes in cells and unicellular organisms?

- What is the role of gravity in the growth and development of plants?
- How does gravity influence postnatal growth and development in animals?
- What are the results of exposure to microgravity over many generations of animal and plant organisms?
- Does exposure of crew to space radiation present a limit to their safe long-term residence in space? What are the damaging effects at tissue level and how can they be minimised?

In exobiology the research will be concerned with questions such as:

- Can microorganisms survive for extended periods in space? Do they, or their immediate precursors, exist in space?
- How did life appear on Earth and has it existed, or does it exist, elsewhere?



Matroshka will be mounted on the outside of the Space Station to study radiation dosages on space-walking crewmembers.

Human Physiology studies have so far concentrated mostly on the fundamental effects of microgravity. They have contributed some new concepts and modified established ideas of body functions, with application in the field of diagnostics and therapeutics for medicine. In the future, studies will be concerned with answering questions such as:

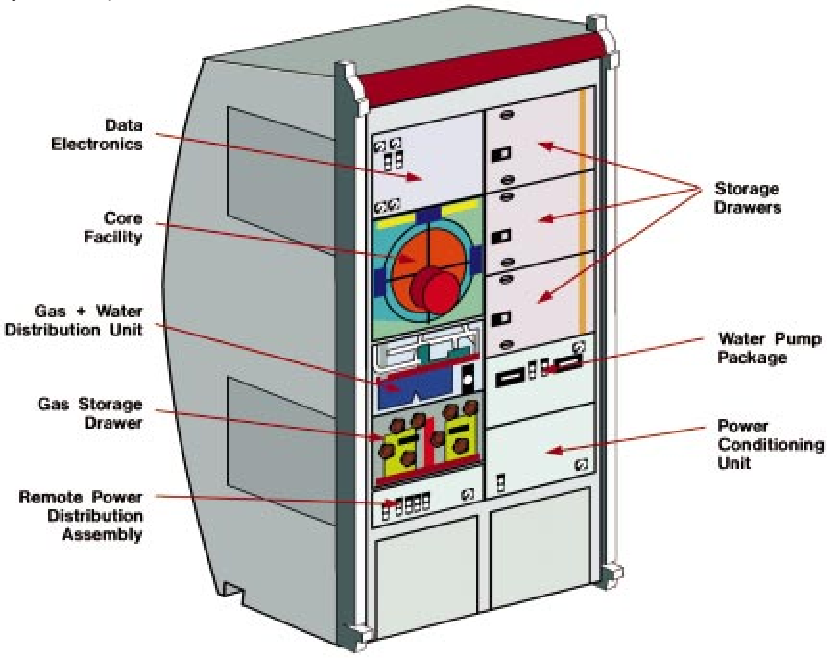
- What are the underlying processes that lead to muscle atrophy and bone loss in microgravity? How can these changes be arrested or slowed?
- What are the detailed integrated mechanisms that adjust and adapt the blood circulatory system to weightless conditions, and what are the effects of long-term exposure to such conditions?
- How exactly is the functioning of the lungs modified and breathing adapted when gravity-controlled gradients are absent?
- What changes are induced in the flow and control of the fluids that percolate through the tissues, and how is the functioning of the kidney affected?
- How does microgravity and spaceflight modify the hormone system conditions and the body's metabolism?
- Is the immune response degraded during flight and what are the reasons for impaired wound healing?
- How exactly does the body adapt to the changed relationships of sensory

The European Physiology Modules will support physiological research aboard the Space Station. (ESA/D. Ducros)

signals from visual, skin, joint and muscle receptors, together with those from the balance sensors, when in weightless conditions? What are the total roles of neural and of multisensory adaptation?

- How do microgravity and the confinement of spaceflight over long periods affect behaviour and performance?
- How can the space physiology results best be applied to aid ground-based studies on bone loss, orthostatic intolerance, muscle atrophy and age-related effects?

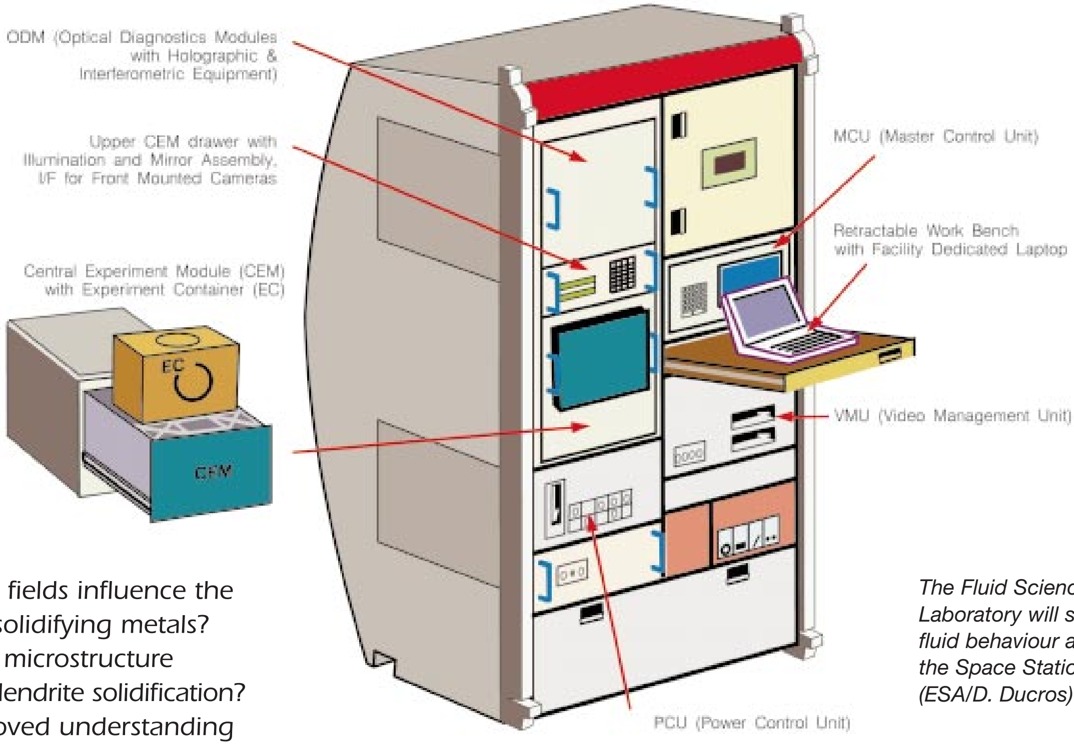
The Material Science Laboratory will investigate solidification physics, crystal growth with semiconductors, thermophysical properties and the physics of liquid states.



Crystal Growth experiments in space have made significant contributions to materials science in general, particularly by improving the understanding of transport processes in crystal growth. These have been translated into improvements in ground-based production methods. Future research will be concerned with:

- How do the dynamics of growth from the melt, including convection, influence the final quality of the crystal? What factors control defect generation in commercially important semiconductor materials such as gallium arsenide and cadmium telluride?
- To what extent does the combined use of magnetic fields and microgravity to control the transport processes in molten metal alloys and semiconductors lead to major improvements in the quality of the final cast alloy or semiconductor crystal?
- What are the growth factors that determine the size and perfection of biological macromolecular crystals? Which of these factors are principally responsible for improving the quality of protein crystals grown in space?
- What influence does the mass transport process have on the perfection of vapour-grown bulk semiconductor crystals and epitaxial layers?

Metal Physics studies will continue to be concerned with growth processes of metals and alloys, improving on earlier studies that led to new insight into the phenomena occurring at the growth front and into the process of metastable solidification. Some of the outstanding questions concern:



The Fluid Science Laboratory will study fluid behaviour aboard the Space Station. (ESA/D. Ducros)

- How do magnetic fields influence the microstructure of solidifying metals?
- What controls the microstructure during cellular or dendrite solidification?
- How can an improved understanding of the process of metastable solidification lead to new materials of industrial application?

Physical Chemistry research has covered a diverse range of studies. In future the questions will relate to:

- How does boiling actually take place? What improvements to industrial processes can be achieved by a better understanding of the process and refined models?
- What mechanisms determine the stability of foams and emulsions? What factors define the transfer of matter across the film interface? How do bubbles and drops migrate?
- How is a solid nucleus created from a liquid or a vapour and how is that process influenced by interfaces and impurities?
- What are the thermophysical properties of the high-temperature and reactive melts from which the industrially important alloys and semiconductor materials are cast or grown? How can these much more accurate values for thermal conductivity, viscosity, surface tension etc be combined with improved models to provide industry with better predictions of product characteristics?

Fluid Physics has gained from microgravity experimentation a greater insight into complex behaviour in instabilities and flows, including the role of interfaces, with wide practical applications. It will continue related work as well as answering questions such as:

- How do flows develop and behave in multiphase systems?
- What is the nature of flows and instabilities that result from the coupling of interfacial phenomena and variable levels of gravitation?
- How is the process and kinetics of wetting and spreading modified by a changing gravitational force?
- What are the detailed processes involved in the diffusive instabilities that result from the coupling between heat and mass transfer in fluids?

Combustion research in Europe has been concerned with several topics of industrial interest, including high-pressure droplet combustion rates, the flammability of high-pressure lean gas mixtures, and flame spreading rates over condensed fuels. Future work is intended to use microgravity conditions to investigate aspects of relevance in energy production, propulsion, safety and environmental issues, as well as the production of materials. Questions that need answering include:

- What are the fundamental characteristics of single droplet and particle combustion in the absence of

convection? What are the ignition, stability limits and flame propagation rates in spray or cloud combustion in the absence of sedimentation and convection effects? How can these data be applied to numerical models to aid in industrial designs?
- What are the mechanisms of soot formation and oxidation in spray combustion? How can this be reduced and applied to minimise pollution from gas turbine and diesel engines?
- What are the various influences of gravity during the self-propagating combustion synthesis production of materials such as foam ceramics and cermets? How can productivity and quality be improved by modifying those influences?

General Physics studies will be concerned initially with questioning:

- How do very small particles aggregate and disperse following collisions in space conditions? How can these experiments best be related to problems in astrophysics and to the many industrial processes involving powders?
- What is the behaviour of such small particles when electrically charged? How do they move and transform into ordered structures called plasma crystals?
- What is the actual improvement in accuracy of the laser-cooled atom clock when operated in microgravity? How can an ISS-based international time reference best be operated to support the wide range of potential users?

Technology-oriented use of the ISS will initially be concerned with using it as a testbed for innovative developments in advance of their application in space systems. In the longer term, the ISS is expected to be used to support technical and commercial operations. Among currently considered activities are those that question:

- How can the ISS be used in a key role as a master control station for future navigation systems by providing timing, based on the ISS-located laser-cooled atom clock and signal links to the constellation of navigation spacecraft?
- Can an antenna/receiver on the ISS, linked to NASA's Deep Space Network and the onboard atomic clock, provide a major improvement in deep-space communications and, in conjunction with interferometric or Doppler systems, greatly improve the accuracy of spacecraft navigation?
- Is it feasible to launch and operate, via tethers, small payload systems from the ISS, in order to place them beyond potential contamination or interference from the Station and thereby enlarge the scope for use of the ISS?
- Can free-flying platforms be used in a similar manner?
- What are the practical problems in introducing electric-propulsion systems into spacecraft designs for orbit transfer, station-keeping and attitude control functions and for interplanetary missions, with reduced launch mass requirements and cost savings?
- Can the new two-phase flow cooling technology be applied to spacecraft design to enable higher power dissipation from the new generation of telecommunications satellites?

- What are the practical problems in implementing high-temperature superconductor-based electronic components in spacecraft systems?
- What is the local dust, gas and radiation environment at the ISS, and what is the long-term effect of that environment on surface materials?

Earth Observation from the ISS is expected to be carried out by instruments that are either large and demanding on resources such that they cannot be readily accommodated on conventional spacecraft, or they will be instruments and techniques using the ISS essentially for testing and proof of concept. Instruments from both categories have been proposed and deal with questions such as:

- What is the effect of large forest fires and volcanic eruptions on the global environment?
- How do changes in the spectral content and total energy of the solar radiation influence the Earth's climate and upper atmosphere chemistry? What are the effects of the short- and long-term variations?
- What are the global spatial variations of wind profiles and how do these change with time? How can such space observations aid meteorological research and predictions?
- How do aerosols and man-made complex molecules enter and move within the Earth's upper atmosphere on a global scale? What is the effect of the breakdown products on upper atmosphere chemistry and the solar radiation that reaches the surface?

Space Science observations from the ISS will tend to be carried out by instruments that benefit from routinely replenishing consumables, such as coolants, and exchanging elements, which will update and improve the quality and range of observations. It will also be used by very large instruments or telescopes requiring complex assembly processes and routine maintenance. Returning instruments to Earth for detailed calibration and delivering samples for detailed analyses are further attractions.

There is a wide range of observations possible from the ISS, addressing questions such as:

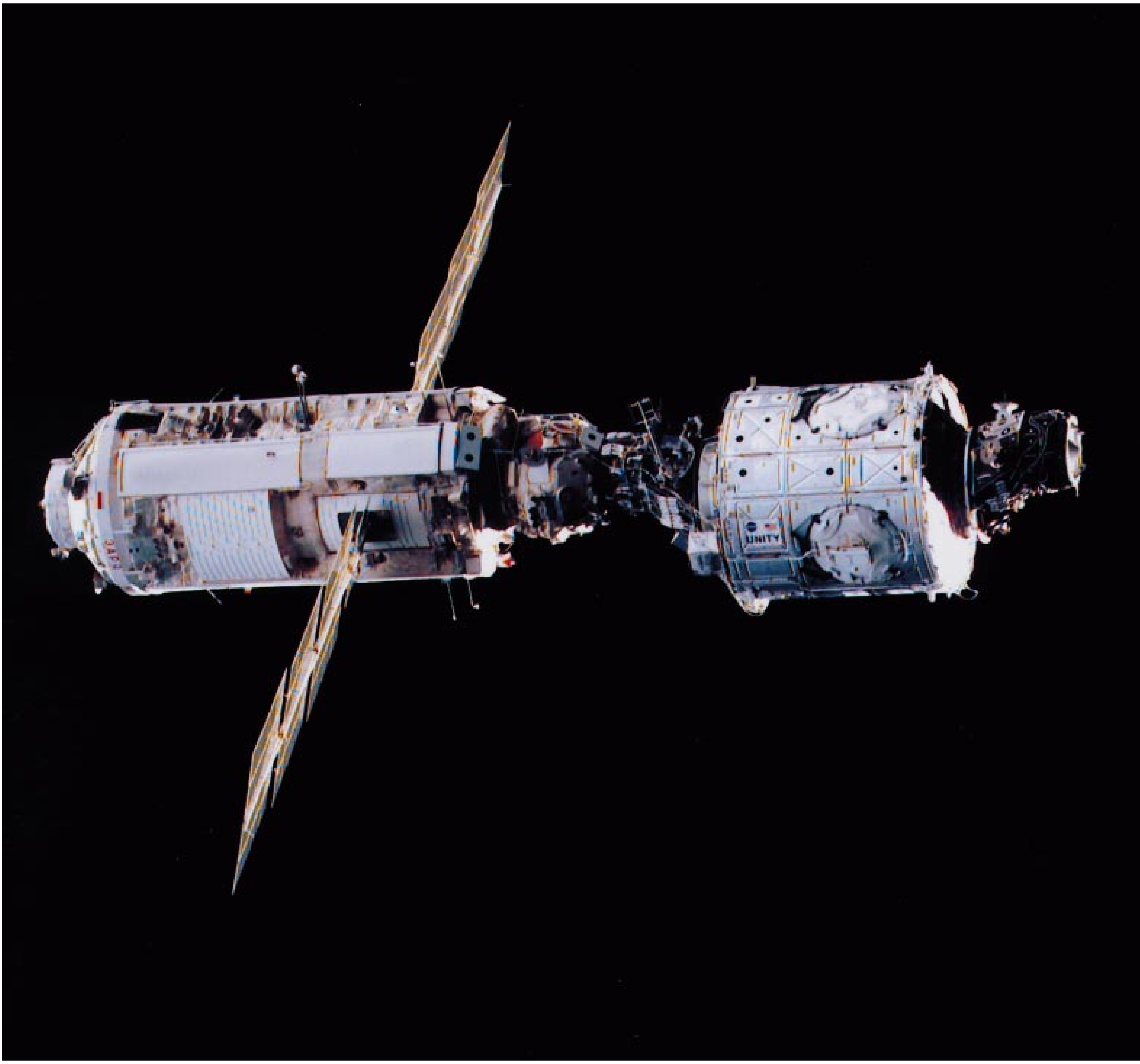
- How does the presence of the ISS affect the local plasma, particulate and atomic species environment?
- Is it possible to distinguish the weak linear polarisation of the cosmic background radiation from the strong synchrotron radiation in our Galaxy?
- What is the nature and origin of the local particulate matter in the Station's orbit? What can be learned of cometary, planetary and exobiology interest from sample capture and analysis?
- What are the origins of high-energy transient gamma-ray emissions?
- What happened between 300 000 years and 2000 million years after the creation of the Universe, when radiation and matter decoupled and neutral atoms formed?
- How did massive black holes originate and how are they accreting?

European Research Facilities Aboard the International Space Station		
First Year On-Orbit	**Facility**	**Research/Applications Area**
1999	Global Transmission Services	Transmission demonstrations
2000	Hand Grip Dynamometer	Human physiology
	Microgravity Science Glovebox (MSG)	Microgravity research
	Minus Eighty Degree Laboratory Freezer (MELFI)	Support to biological research
	Advanced Protein Crystallisation Facility (APCF)	Protein crystal growth
2001	Matroshka	Active/passive dosimetry
2002	Material Science Lab (MSL) (in US Lab)	Materials science research
	Modular Cultivation System (MCS)	Biological research
	Muscle Atrophy Research & Exercise System (MARES)	Human physiology research
	Percutaneous Electrical Muscle Stimulator (PEMS)	Human physiology research
	Atomic Clock Ensemble in Space (ACES)	Fundamental physics
	Technology Exposure Facility (TEF)	Space technology
	Exposure Unit for Exobiology (Expose)*	Exobiological research
	Sky Polarisation Observatory (Sport)*	Astronomy
2003	Biolab	Biological research
	Fluid Science Laboratory (FSL)	Fluids science research
	European Physiology Modules (EPM)	Human physiology research
	European Drawer Rack (EDR)	Various, e.g. Protein crystallisation; Microgravity environment
2004	Material Science Lab (MSL) (in Columbus)	Materials science research
	Focus Intelligent Fire Detection Infrared Sensor Payload	High-temperature detection
	Solar Package**	Solar physics
2004+	Atmospheric Laser Doppler Instrument (ALADIN)	Earth observation
	Near-Earth Object Telescope	Astronomy
	Large X-ray Telescope (XEUS)	Astronomy

*Expose and Sport (collectively: Export) may in final planning by the European Utilisation Board
**the Solar Package may in final planning by the EUB be exchanged for Export in 2002

Detailed Research/Applications Topics
Transmission of highly accurate time and data signals to ground users
Monitor hand muscle strength changes
Multiuser glovebox for microgravity research
Deep freezing of biological samples before/after experiments
Protein crystals of high quality for X-ray analysis
Measurement of depth dose radiation distribution in human body, particularly during Extra Vehicular Activity
Solidification physics; Measurement of thermophysical properties; Crystal growth by Bridgman techniques
Research on plants and small aquatic animals
Changes in strength of isolated muscle groups around joints
Changes in muscles in weightlessness
Use of laser-cooled caesium clock in microgravity giving 100-fold increase in accuracy. Applications in atmospheric physics, geodesy, navigation, telecommunications, relativity tests
Modular accommodation; Material properties; Cosmic radiation; Plasma environment; Atomic oxygen; Robotic arm/servicing of payloads
Exposure of organic molecules and microorganisms to unshielded solar UV radiation and to other space environment parameters (vacuum, cosmic radiation). Study photochemical processes, conclusions on the origin and evolution of life and the survivability of microorganisms in space
Polarisation of the Sky Diffuse Background Radiation 20-70 GHz
Cells, cell tissue, microorganisms, small plants, small invertebrates; Mechanisms of development, radiation damage, graviperception
Flows and instabilities induced by surface tension gradients and thermal radiation forces; double diffusive instabilities; interfacial tension and absorption; mechanisms of boiling; critical point phenomena; crystal growth; directional solidification, etc
Impairment of muscle structure and function; Impairment of bone remodelling and decalcification; Ventricular performance and regulation of blood pressure and volume; Endocrine components of fluid balance and kidney function; Regional interstitial fluid dynamics; Lung ventilation/perfusion and chest-wall dynamics; Multi-sensory integration and neuronal adaptation; Otolith organ and space adaptation syndrome
Solidification physics; Measurement of thermophysical properties; Crystal growth by Bridgman techniques
Detection of forest fires, volcanic eruptions, pollutant emissions
Long-term monitoring of solar spectral irradiance; Variation of solar constant. Applications to atmospheric modelling, chemistry and climatology
Accurate wind field measurement and vertical profiles on global scale for numerical weather prediction and climatology studies
Detection of near-Earth asteroids/comets likely to pose collision hazards for Earth
Investigation of high-energy astrophysics associated with early evolving Universe

(EUB) be exchanged for the Solar Package in 2004.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