SCIENTIFIC AMERICAN PRESENTS

LOOKING UP: EUROPE’S QUIET REVOLUTION IN MICROGRAVITY RESEARCH

Man-Made Meteorites
Testing the survival of rocks and microbes

Hope for Hypertension?
Microgravity can lower blood pressure

The Complexity of Plasma
Soft matter study advances when free from gravity

It’s All Relative
Probing the limits of Einstein’s theories

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Astronauts are the heroes of our time. Wherever they show up, they attract the curiosity and admiration of the public. On television, we see them floating through a space station; we see them exercising, eating and working outside the station attaching or fixing something. Sometimes they are stationed in front of a console, pulling a drawer or pushing a button, but frankly, we do not have any idea what they are doing there or what is happening inside those racks. This Special Presentation of *Scientific American*, devoted to life and physical sciences research in space, is meant to help remedy this deficiency.

My own field is space plasma physics. I have been engaged in experiments exploiting the electromagnetic forces of near-Earth space acting on artificially injected plasma clouds. These experiments are very different from the research discussed in this publication. Here one exploits the near-weightless (microgravity) conditions found in orbital flight to study the behaviour of physical and biological systems in the absence of the effects of gravity. The use of microgravity is what makes this research unique compared with the more classic space sciences of plasma and solar physics, astronomy and the planetary sciences.

As a former Chairman of the European Space Science Committee of the European Science Foundation, I have had the privilege of being able to survey the whole gamut of European space sciences and consequently been able to gauge for myself its strengths and weaknesses. In the course of this, I gradually became familiar with the work of European scientists in the microgravity and related fields. What struck me first was the enormous range of scientific areas involved, such as crystal growth, alloy formation, soft matter physics, the wide field of fluid sciences, relativity physics, the highly important field of human and plant physiology and finally the fundamental studies of the behaviour and survival of biological systems at the cellular level, not only under microgravity, but also under exposure to the harsh space environment.

As I acquainted myself with this research, I also came to realise how in recent years this work had acquired the mantle of top-class science, yet had not received the exposure at the popular science level that I felt it deserved. As Chairman of the Advisory Committee on Human Spaceflight, Microgravity and Exploration of the European Space Agency (ESA), I was therefore highly gratified when *Scientific American* agreed to produce a Special Presentation devoted to this work by European scientists, often in collaboration with scientists from other countries.

Having seen the highly informative articles that have resulted along with the fine and captivating artwork and the excellent editorial work of *Scientific American*, I can only wholeheartedly recommend this highly readable Special Presentation entitled “Looking Up: Europe’s Quiet Revolution in Microgravity Research” to anyone seeking a deeper understanding of this fascinating area of scientific research.

Gerhard Haerendel
Chairman of the Advisory Committee on Human Spaceflight, Microgravity and Exploration (ACHME) for ESA
Preface ................................................. 1
   By Gerhard Haerendel

INTRODUCTION
A Letter to Readers  ......................... 4
   By John Rennie

PERSPECTIVES
Life in Orbit ......................................... 6
   By Thomas Reiter
The personal and professional rewards of space exploration

ASTROBIOLOGY
Meteorites: Stones with Stowaways? ........ 8
   By Frances Westall and
   Rosa de la Torre Noetzel
Can organisms be transported from one planet to another and survive both space conditions and atmospheric entry to impregnate the host planet with new forms of life? Scientists explore whether Earth was colonised by microscopic hitchhikers.

HUMAN HEALTH
Counteracting Hypertension with Weightlessness? ........ 16
   By Peter Norsk and John M. Karemaker
Many of us have been told to lose weight to lower our blood pressure, but going weightless? Studies of astronauts show that gravity does contribute to cardiovascular stress.

Clinical Immunology in New Frontiers ............ 24
   By Alexander Choukèr, Boris Morukov and Clarence Sams
When thinking big, we must also remember to think small, especially when we need to fend off illness in space. As Victor Hugo once said, “Where the telescope ends, the microscope begins; and who can say which has the wider vision?”

SPECIAL REPORT: Bone Loss in Space .......... 32
Sticks and stones may break your bones, but underuse will make them brittle. Like extended bedrest, an environment without gravity reduces the workload on bones and makes them weaker. Because research in this area is extensive, two articles are presented here to illustrate different approaches being taken to understand—and combat—these effects.

Zero Gravity: Bad to the Bones
   By Laurence Vico and
   Christian Alexandre

Our Sensitive Skeleton
   By Rommel G. Bacabac, Jack J.W.A. Van Loon and
   Jenneke Klein-Nulend
Breaking the Mould:
Metallurgy in Microgravity . . . . . . . .  68
By Hans J. Fecht and Bernard Billia
Factories floating in space? Not quite, but the next giant step in metal processing technology may come from an unexpected source: the ISS.

Shake, Rattle and Roll:
Using Vibrations as Gravity . . . . . . .  74
By Daniel Beysens, Pierre Evesque
and Yves Garrabos
In space, you can’t toast your successes with Champagne or sweep sand into a pile to clean up. So how can you make matter behave?

The Complex Matter of Plasma . . . . .  82
By Gregor Morfill and Hubertus Thomas
The 1993 discovery that complex plasma can exist as soft matter changed the face of physics. Since then, research into its properties and behaviours has exploded, and experiments on the ISS have led to a number of discoveries that could not have been made in the presence of gravity.

Timing Gravity . . . . . . . . . . . . . . . . . .  50
By Stefano Vitale, Christophe Salomon
and Wolfgang Ertmer
High-precision experiments performed in space will put some of Einstein’s theories to the test.

Moving in Flow-Motion . . . . . . . . . . .  60
By Michael Dreyer, Ilia Roisman,
Cameron Tropea and Bernhard Weingartner
A malfunctioning fuel pump and a harrowing near-disaster at Heathrow Airport illustrates the necessities of understanding fluid flow dynamics. Removing gravity from this complex equation allows for new and exciting research in this area. May the capillary force be with you!

The Puzzle of Plants . . . . . . . . . . . . . .  92
By Dieter Volkmann, Anders Johnsson
and František Baluška
Roots grow downward while stems shoot upward. Clearly, plants “sense” gravity, but how? Years of research in gravitational biology have yielded some remarkable new insights—and striking contradictions.

Bibliography . . . . . . . . . . . . . . . . . . . . . .  100
Fifteen years ago or so, I had the occasion to step out of a perfectly good airplane while it was two and a half miles in the air. You have no doubt correctly surmised that I was wearing a parachute, for which I seem to recall being extremely grateful at the time. Between the alternating waves of terror and exhilaration, as I found myself falling faster and farther than I ever had before, I had plenty of opportunity to appreciate a profound truth: gravity rules our lives in ways we often take for granted.

Strangely enough, gravity is the weakest force in the universe. True, it can feel powerful when you are, say, skydiving or struggling to push a stalled car uphill, and the fact that it holds together solar systems and galaxies lends it dramatic flair. Nevertheless, compared to the other fundamental forces of nature—electromagnetism and the two nuclear ones that bind atomic nuclei—gravity is a piker. Every time you take a step, you move your body easily against the gravitational tug of the entire Earth. Gravity just seems strong because its force never self-negates over distance in the way that the positive and negative poles of electromagnetism do.

Thus we experience gravity everywhere, which for centuries impeded our ability to conduct experiments aimed at better understanding it.

That has changed, thanks to modern technology. We can now send people and instruments into space to study weightless, free-fall environments. Scientists are discovering precisely how gravity shapes the structure of various materials, including the tissues that make up our own bodies, and how it is involved in the complex dynamics of flowing fluids at larger and smaller scales. As the human race continues its exploration of space, and possibly even its eventual colonisation of it, we will need to know what life outside our familiar 1g means.

The articles in this collection provide a wonderful overview of such scientific explorations into microgravity and related phenomena, and I hope you will enjoy them. Your feet may stay planted on the ground but you are still in for an exciting intellectual trip. Geronimo!

John Rennie, editor in chief
Scientific American
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always experience déjà vu when telling children of my adventures in space. I remember myself as I watched Neil Armstrong walking on the moon and decided, “Yes, that is what I want to do.” Not that there were many obvious and immediate chances for Europeans to become astronauts. Building a suitable background by studying aerospace technology and getting into aviation came first, and then when the opportunity actually came, I didn’t have to think for a second about what my answer would be.

I am often asked why I took on such a risky life. For me, the benefits of a career in spaceflight definitely outweigh the risks—and those benefits include not only the scientific knowledge gained from our experiments, but also the cultural and personal rewards. I believe people are inherently curious, and this desire to explore the unknown is something I very much feel and follow. To me, exploration is worth the risks.

With the International Space Station nearing completion, all of the agencies involved in the ISS programme are looking forward to the moment when we can really utilise the station and all the capabilities of its multifunctional research laboratory. People want to know about life in orbit. Having experienced six months on Mir as well as a long mission on the ISS, I can say there is a general similarity in the daily routine. There are many differences, however, between the two stations. Everything is much more advanced aboard the ISS, much more modern. Inside we have quite a bit more space than we had on Mir. We now have two Mission Control Centres we can talk to, and we can talk to them almost 24 hours a day. On Mir we could talk to the Russian control centre only at certain times. Last but not least, from a personal point of view, the food has become a bit more international. We have more items we can choose from, which becomes quite important if you are staying on the station for a long time.

One advantage of having several people on board the station is that all astronauts work together to increase the station’s scientific output. With more people, we have more time to perform the scientific programme. Opportunities will continue to arise to install new scientific hardware both internally and externally, and the operational capabilities of the station will be expanded even further in the future. Of course, it is always the objective of each crew member to maintain the station efficiently so that it can run as smoothly as possible.

During my mission on the ISS, we took part in an experiment called the Materials ISS Experiment or MISSE. We installed two platforms containing some specific materials that would then be exposed to the conditions of low Earth orbit. These platforms will be retrieved later, when they will be examined to see how this environment affects these materials. We also installed a so-called floating point measurement unit, which is a scientific device on the S1 truss segment. Finally we set up one technology experiment that will use an infrared camera on future shuttle flights to determine any defects on the exterior of the shuttle. Most of the experiments on board are from the areas of life sciences, biology, physics, astrophysics and technology. So a pretty wide band of science is covered.

One interesting physics experiment involves plasma crystallisation. A plasma is generated, dust particles are injected and then those particles inside the plasma behave like molecules in a crystal. A very new area of research, these results will be important in different areas of fluid physics, solid-state physics as well as other areas. In fact, we ran this experiment not only once but repeated it during the mission. For the life sciences, we carried out investigations related to the human vestibular system, the cardiopulmonary system and the skeleton; and in biology we performed an experiment related to the generation of protein crystals.

Our research in life science serves two purposes: first, to better understand certain diseases that exist here on Earth and help to find cures for them; and second, in view of the continuing exploration of space, to prepare us for long-duration missions in future decades, maybe to our neighbour planet Mars. Before we attempt to travel that distance, we definitely need to understand how to counteract the effects of weightlessness.

Speaking of which, we astronauts are always asked about living in a weightless environment. It’s indeed true that when you get into space, the perception of weightlessness is simply very, very nice. It’s a unique feeling not to perceive the weight of your own body, to float around and to use the whole space inside the station. You can work on the floor or on the ceiling without any difference. However, the drawback is you don’t use your muscles
as much in space as you use them here on the ground—even when we are only sitting up, we still have to exercise some muscle control to hold ourselves up against gravity. Of course, when we are walking or standing, we use them even more. This is not the case in weightlessness, however, where we lose muscle mass with lack of use. Weightlessness also has a similar negative effect on bones. Our bones immediately start to lose calcium once we get into orbit, which makes bones more brittle. In addition, the weightless conditions combined with cosmic radiation affects the central nervous system and immune system. How and why these effects occur needs to be better understood.

As you can see, the ISS is not just a “plaything” in space; nor is it an expensive “white elephant.” It is an essential part of the human endeavour to seek greater knowledge of the universe as well as to take advantage of microgravity to find a better understanding of how gravity affects on our life on Earth.
LOOKING UP: Europe's Quiet Revolution in Microgravity Research

Can organisms be transported from one planet to another and survive both space conditions and atmospheric entry to impregnate the host planet with new forms of life? Scientists explore whether Earth was colonised by microscopic hitchhikers.

By Frances Westall and Rosa de la Torre Noetzel

In the summer of 1996, the equivalent of an earthquake shook the scientific world. David McKay of the Johnson Space Centre (JSC) in Houston, Texas, and his colleagues announced in the lay press and in a scientific paper published in the prestigious journal Science that they had found traces of Martian life in a meteorite from Mars. This announcement led to a spate of rebuttals, confrontations, and new studies, as well as provided an incredible stimulus to Mars research—in particular, the search for life on Mars.

Why from Mars?

It was only when 1.3 billion-year-old meteorites of volcanic rock were found that scientists realised they must therefore have come from a geologically active body. Analysis showed that these meteorites contained trapped gases identical to those in the Martian atmosphere. The rocks had been ejected from the surface of Mars when some large body of matter crashed into the planet. They then went into orbit around the sun for several million years before falling to Earth.

More than 10 years after their initial announcement, the JSC team still maintains that they have evidence for life (although they have had to back down on a number of their original lines of evidence) ... and the rebuttals continue. The present situation is a stalemate, and we probably won’t know if there is or was life on Mars until we get the RIGHT rock back from Mars.
Microorganisms can live in very diverse environments, including cracks in volcanic rocks.

Their ability to survive begs two questions: was there ever life on Mars, and could microbes have been carried to Earth on meteorites?

Using a space capsule to create artificial meteorites, scientists placed sedimentary rocks in sample holders on the heat shield to test if they would survive atmospheric re-entry.

Some rock samples survived and developed the dark fusion crust typical of real meteorites, but microorganisms have not yet made it through Earth’s atmosphere.

—The Editors
Microbes, Please—
On the Rocks

The rock that McKay and his group are still analysing in painstaking detail is the equivalent of terrestrial basalt, a volcanic rock. In fact, all the meteorites from Mars (38 have been identified to date) are igneous rocks, which are rocks that have consolidated from magma, molten rock ejected during volcanic eruptions.

Since the 1996 announcement and the blossoming of astrobiology (the search for the origin and existence of life in the universe), numerous investigations have shown that microbes can live in the most diverse habitats and environments, including cracks in cooled volcanic rocks. However, evidence against McKay and colleagues hardened when it was discovered that his rock formed about 4.5 billion years ago when the planet of Mars first consolidated. How could such an ancient rock contain traces of life when the planet had only just condensed?

It later turned out that the minerals filling the cracks in the rock where the supposed microbial traces were found were deposited by low-temperature fluids some 3.9 billion years ago. This was a period when Mars had significant quantities of water on its surface and when its surface was habitable. Later (between 3.8 and 3.5 billion years ago) the surface of Mars became hostile to life; however, life may still survive in the subsurface.

No Stone Unturned

In the same year that McKay was making his announcement, René Demets, project scientist for space biology at the European Space Agency, also announced the discovery of a Martian meteorite—ALH 84001 (full name Allan Hills 84001) was found in 1984 in Allan Hills, Antarctica, by US meteorite hunters. Although it appears absolutely normal with 80% of its surface covered by the standard dark fusion crust, this meteorite made headlines in 1996 when scientists announced it contained traces of life—a claim still hotly debated.

A Hitchhiker’s Guide to the Galaxy

A meteorite’s journey from Mars to Earth was long and violent. First, an asteroid or other large body crashed into the Martian surface with enough force to eject chunks of the planet into space. After orbiting the sun for millions of years, these Martian meteorites then survived the heat of atmospheric entry to finally land on Earth.
Research and Technology Centre (ESTEC), the technical heart of the European Space Agency, developed a plan with André Brack at the CNRS in France. Was there a way to find out more about what might survive a journey through the Earth’s atmosphere without waiting for another suitable Martian meteorite to land? Their solution: to expose mineral samples to the environment created on the heat shield of a recoverable Foton capsule (a Russian spacecraft) when it re-entered the Earth’s atmosphere. ESA scientists had used the unmanned Russian Foton capsule’s heat shield to test materials before, but never in the name of astrobiological research.

This growing interest in Europe in astrobiology led to a completely new series of experiments: the Stone series. The objective was, and is, to test the ability of different types of sedimentary rocks with a similar composition to those found on Mars (such as sandstone) to survive during entry into the Earth’s atmosphere. As the experiments progressed, however, this goal has broadened to look at the wider possibility of microorganisms being carried between planets. On the right, “A History Set in Stone” gives a brief overview of the early Stone experiments 1–4, while this article concentrates on the two most recent experiments, Stone 5 and 6.

**Stone 5**

Led again by André Brack, Stone 5 was launched in 2005 and proved a great success. Four rocks were embedded in the heat shield of a Foton 12 capsule around the point where the spacecraft is subjected to the highest heat stress upon atmospheric entry.

**A HISTORY SET IN STONE**

The series of Stone flights began in 1999. Their objective was to simulate a meteorite entry into the Earth’s atmosphere by placing sedimentary rocks in sample holders on the heat shield of the unmanned Foton Russian spacecraft. Upon the craft’s return to Earth, these “artificial meteors” would then be recovered and analysed.

**STONE 1**

Launched 1999 with 3 rocks placed on heat shield

- Control sample: Dolerite, a basalt with similar characteristics to stony meteors (formation of a black fusion crust confirms that re-entry speed was high enough to melt rock, as with real meteors)
- Natural sediment: Carbonate sediment and mixed basalt
- Artificial sediment: Basalt and gypsum created to simulate Martian sediment

**Results**

- Control sample lost during flight
- Two test samples showed alteration due to high temperature; They produced CO₂ and calcium oxide; Neither had a fusion crust
- Loss of the control rock meant that the speed of re-entry could not be proved

**STONE 2**

Crash landed—rocks not recovered

**STONE 3**

Not flown

**STONE 4**

Exploded after launch

An illustration of the Russian Foton capsule used to simulate atmospheric entry. Sedimentary rocks were placed on the heat shield, sent into space and then brought back to Earth to test their ability to survive a journey through our atmosphere.
One rock was the same type of igneous volcanic rock as a real meteorite—basalt—to act as a control. One of the most characteristic features of stony meteorites is their dark-coloured fusion crust of molten rock, which is created by the intense heat of atmospheric entry. If a fusion crust formed on the basalt sample, that would mean that the temperatures endured during atmospheric entry were high enough to melt the rock and thus the similarity with real meteorites would be validated. The basalt control sample came back with a very acceptable fusion crust, showing that the speed of re-entry at 7.6 km/sec provoked a sufficiently high temperature to melt the exterior of the rock.

All four rocks in this experiment survived atmospheric entry. Apart from the basalt, they included two sediments: a dolomite (limestone rich in magnesium carbonate) and a sandstone (quartz sand cemented by calcium carbonate). The fourth rock was rather unusual; it was an impactite, which is a rock that has been impacted by a previous meteorite as it hit the ground. It was brought from the Haughton Impact Cra-

**We probably won’t know if there is or was life on Mars until we get the RIGHT rock back from Mars.**
ter on Devon Island in the Northern Territories of Canada. These rocks tend to be very porous because they melt during impact and the intense heat causes their components to alter, during which gases are liberated (a process called devolatilisation). Such rocks would be common on the surface of Mars.

To test the heat sensed during atmospheric entry, Gabriel Bourrat of the University of Lausanne in Switzerland ingeniously placed thermal probes consisting of minerals that melt at specific temperatures inside the dolomite. Based on which materials melted within the dolomite rock, temperatures went beyond 271°C but not as high as 630°C. In addition, a fusion crust did form on the surface of the dolomite (in contrast to Stone 1, see “A History Set in Stone,” page 11), which corroborated the result of the formation of fusion crust on the basalt and indicated that these experiments did simulate meteorite entry, despite the lower entry speeds.

Earth “Impregnated” with Life?
Another aspect of the Stone 5 experiment was of particular relevance for astrobiology. The experiment addressed not only the survivability of rocks but also the survivability of living organisms within or on the stones, a concept called “panspermia,” which poses the question: “Can organisms be transported from one planetary body to another and survive both space conditions and atmospheric entry to impregnate the host planet with new forms of life?”

The idea of microorganisms living in rocks (called endolithic microorganisms) is not unusual—volcanic rocks can be an excellent source of nutrients for certain types of microorganisms.

One type of endolithic microorganism can live under the surface of a (relatively) transparent rock and uses sunlight to produce energy. Called *Chroococcidiopsis*, their rocky habitat protects them from the intense harmful UV radiation that is found at both the North and South poles, where these types of organisms are often found. The porous impactites described above are also ideal habitats for such organisms, and the surface of the porous rock used in Stone 5 was soaked in a solution containing the spores of this type of endolithic bacterium. Furthermore, all the rocks carried a mix of different microorganisms, endolithic bacteria and fungi that had been placed inside tiny holes drilled into the back of each 1-cm thick rock sample.

The idea to test the hypothesis of panspermia was good, but unfortunately, the microorganisms did not survive entry into the atmosphere. Those on the surface of the impactite disappeared as the surface was vaporised (ablated) during entry, and those in the holes in the backs of the rocks were killed by the intense heat of entry. Two lessons were learned here. The first is that five millimetres of rock cover are not sufficient to protect the microorganisms from the intense heat produced during atmospheric entry. The second is that the origin of the photosynthetic—that is sunshine-using—microorganisms on Earth had to have been a terrestrial phenomenon because such microorganisms that live close to the rock surface cannot survive atmospheric entry.

**Ultraviolet-Resistant Plants**
The same Foton capsule that carried Stone also carried another experiment called Lichens designed to test the panspermia hypothesis. Attached to the capsule was a canister, Biopan 5, which opened once the capsule had reached the required altitude to expose its contents to the harsh conditions of space. Within the canister were live lichens that were exposed for 16 days to full solar and cosmic radiation as well as extreme dryness due to the vacuum conditions of space. Lichens are not single organisms; they consist of a fungal element and either photosynthesising bacteria or algae that live together in a symbiotic relationship. Lichens are extremely resistant to UV radiation and can survive at high altitudes above 2000 metres where no other plants can survive; and like the endolithic photosynthetic bacteria of the Stone 5 experiment, they can also live at high latitudes in the Polar regions. They were used as a test case in this experiment because of their UV resistance.

Despite their known resistance to UV radiation, it was still a surprise to discover that, after 16 days of exposure to space conditions and harsh UV radiation, all the lichens showed the same photosynthetic activity after the flight as before exposure to space. The team wondered if, however, there had been some subtle damage to the microbial cells as a result of this exposure. They proceeded to make minute microscopic studies of the cells with powerful electron microscopes but could still detect no signs of degradation. It was only when they used a simple biological test called a live/dead test, which can differentiate the number of live cells compared to dead ones, that they were able to detect the slightest sign that there were, not surprisingly, more dead cells after the flight than before.
To Boldly Go Where Others Cannot

The sheer resistance of the fungi to space radiation, a condition detrimental to bacteria and other microorganisms, is astounding. How do they survive? It seems that the thick outer coating around the lichens, their cortex, provides them with adequate protection against solar radiation, at least for 16 days.

The lichens had yet another story to tell after their space trip. Space is a high vacuum environment and any matter containing water, such as microorganisms, are subject to an extreme degree of moisture loss called desiccation. The lichens were no exception. However, 24 hours after returning to Earth and in the presence of water, the lichens recovered their full metabolic activity.

The Stone 5 and the Biopan 5 experiments provided interesting information regarding the survivability of microorganisms in space, but they also highlighted the difficulty of returning the microorganisms alive into the Earth’s atmosphere. Stone also confirmed, once again, that sedimentary meteorites can survive atmospheric entry. However, it left us wondering about the types of sediments that can resist the trauma of entering the atmosphere and if it were possible for microbes that could survive space conditions to get through this barrier alive.

Stone 6

Another experiment, Stone 6, (led by author Frances Westall) was designed to address these outstanding questions. Apart from the basalt control, one type of sediment used as a potential Martian meteorite was volcanic sandstone dating from an epoch on Earth when there was still water on Mars and the possibility that life could exist at its surface.

This 3.5 billion-year-old volcanic sandstone from the Pilbara in Australia was deposited in environmental conditions that were similar to those of early Mars, conditions that are considered extreme by present day standards (no oxygen, no ozone layer to protect the surface from harmful UV radiation, much volcanic and hydrothermal activity and many impacts from asteroids, meteorites and comets). This sounds like a catastrophic scenario but it was on this early planet Earth (and maybe on Mars) that life appeared and thrived. Traces of this early life occur in fossil form in the volcanic sands that hardened into rock. Given the similarities in the early environments of Mars and the Earth, we hypothesised that these ancient Earth sediments with their traces of fossil life would be ideal analogues for Martian rocks from its “warmer and wetter” Noachian period some 4.5 to 3.5 billion years ago.

Another rock that “flew” as part of Stone 6 was a piece of ancient lake sediment, about 400 million years old from the Orkney Islands off Scotland. The intriguing aspect of this rock is that it is rich in the organic remains of life forms that lived in and around the lake. These remains are the molecules of the degraded components of the dead organisms. We wanted to test whether this type of sediment containing only the molecular organic remains of life could make the ultimate test, survival of entry into Earth’s atmosphere, had it indeed made the journey from Mars.

The last rock in the collection was a piece of granite from the mountains of Spain that was injected with lichens and placed on the heat shield of the Foton capsule to see first whether they survived in space, and then whether they could survive atmospheric entry as well. This would be the ultimate step in the panspermia hypothesis. Just to make sure that these microbes really did thrive well in space, a variety of lichen species communities and endolithic bacteria were placed in another Biopan canister for inclusion in the same experimental flight.

In addition, Stone 6 built on the lessons learned from Stone 5 where the rocks had not been thick enough to protect the microbes during atmosphere re-entry. For this experiment, we engineered thicker 2-cm “chariots” for our microscopic hitchhikers that were representative of the type of rock on Mars at the time in question. Endolithic bacteria were placed on the rear of the rocks.

Back on Earth

Although the basalt rock sample was lost, the others had survived. The 3.5 billion-year-old reconstituted volcanic sandstone from Australia had lost 12 millimetres in thickness but had gained a respectable fusion crust, albeit a creamy colour, unlike the dark fusion crusts of the basalts. Chemical changes in the space cement used in the reconstitution of this rock proved that the temperatures during entry were in excess of 1700°C. The lake sediment full of the molecular organic remains of living organisms had turned into a rather un-appetising green glassy mess, but it had also partially survived.

To our disappointment, however, the bacte-
Stone 6 Results

<table>
<thead>
<tr>
<th>Basalt Control</th>
<th>Volcanic Sandstone</th>
<th>Lake Sediment</th>
<th>Granite</th>
<th>Biopan Canister</th>
</tr>
</thead>
<tbody>
<tr>
<td>Igneous volcanic rock similar to a real meteorite</td>
<td>3.5 billion years old from the Pilbara in Australia</td>
<td>400 million years old from the Orkney Islands off Scotland</td>
<td>From the mountains of Spain</td>
<td>Various lichen species and photosynthetic cyanobacteria placed in Biopan container</td>
</tr>
<tr>
<td>Mounted on Foton capsule</td>
<td>Was formed when Earth conditions were similar to those on Mars</td>
<td>Contained degraded organic remains of life and live endolithic bacteria</td>
<td>Injected with lichens</td>
<td>All life survived</td>
</tr>
<tr>
<td>Formation of dark fusion crust indicates similar re-entry temperature to a real meteorite</td>
<td>Reconstituted to be 2 cm thick, endolithic bacteria placed in rear of rock</td>
<td>Partially survived, but became a green glassy mess on re-entry</td>
<td>Only some pieces of molten rock turned to glass survived</td>
<td></td>
</tr>
<tr>
<td>Sample was lost</td>
<td>Lost 12 mm in thickness, but gained a creamy-coloured fusion crust</td>
<td>Bacteria did not survive</td>
<td>Lichens did not survive</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bacteria did not survive</td>
<td>Study to determine if the fossil remains survived is ongoing</td>
<td></td>
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</tr>
</tbody>
</table>

Fotón-12 Stone sample holder after return to earth.

3.5 billion-year-old Australian sandstone recovered from Stone 6.

About the Authors

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References

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2. But the preliminary observations are very encouraging.

About the Authors

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Many of us have been told to lose weight to lower our blood pressure, but going weightless? Studies of astronauts show that gravity does contribute to cardiovascular stress.

By Peter Norsk and John M. Karemaker

In this age of heightened health concerns, most people are acutely aware of their salt and fat intake, and the effect of modern lifestyle on blood pressure. One factor that also affects circulation but that doesn’t often register, as it is—for the most part—an unchangeable constant, is gravity.

When we are standing, walking or even sitting upright, an appreciable amount of blood settles in the lower parts of the body: the abdomen, buttocks and legs. If the body were not able to counteract these effects and ensure that the brain and other organs were sufficiently supplied with blood at all times regardless of body position, we would be unable to stand or sit upright. It is our central nervous system which provides control over blood pressure (see Figure 1).

If you’ve ever witnessed someone faint dead away from a standing position, this startling occurrence is the result of a failure in the blood pressure control system. In such a case, the force of gravity is strong enough to overpower the free-flow of blood. The most efficient life saving procedure in this case is to place the sufferer immediately in a horizontal position so that blood can again flow more freely back to the heart and hence to the brain.

In the near-weightless conditions of space, gravitational stress is absent. Because gravity is not pulling fluids into the lower areas of the body, these fluids are distributed into the upper areas of the torso more than is usual on Earth. Blood moves more freely from the lower to the upper parts of the body, (over-) filling the heart and lungs and straightening out the facial wrinkles that the astronauts developed over years on Earth. This is what the astronauts call “puffy face and chicken legs” syndrome.

Does Gravity Affect Blood Pressure?
How does the everyday stress of gravity affect blood pressure and fluid volume control in the human body? Studies have shown that blood pressure and fluid volume control are sensitive to changes in gravitational stress. This background became the basis for experiments that took advantage of the weightless conditions on the International Space Station to look at how gravity on Earth...
Counteracting HYPERTENSION with Weightlessness?
influences human blood pressure control as well as shed light on the integrated systems involved in blood pressure regulation.

The results have been surprising and in some cases appear to contradict the expected responses. While they have provided a greater understanding of the effects of gravity on blood pressure control, they have raised other questions surrounding fluid volume control and endocrine responses. Continued research to find the answers to these and other questions could someday indirectly contribute to the development of therapies for high blood pressure, or hypertension, here on Earth.

**Blood Pressure on Earth**

In basic terms, blood pressure refers to the force exerted by circulating blood on the walls of blood vessels. The workhorse muscle of the heart pumps the blood from its ventricles through the arteries to all peripheral tissues of the body, where it feeds the tissues and then returns to the heart through the veins. The heart and all the interconnected vessels are dynamic and work in unison for efficient transportation of blood.

When we are upright on Earth, the heart beats faster than when we are lying down, and the small peripheral blood vessels (small arteries or arterioles) in skin, fat, muscles and gastrointestinal organs are more contracted. This contraction increases the vascular resistance and compensates for a decreased cardiac output—the volume of blood pumped away from the heart by the ventricles. In this way, blood pressure at the level of the heart is unchanged or even increased despite the drag of gravity on the blood column.

**Nervous Responses**

A fast-responding nervous control system is responsible for any acute adjustment of blood pressure that becomes necessary when we are upright, when we exercise or when we change posture or position. The control system consists of a network of blood pressure sensors.
in the upper chambers of the heart (the atria), in the main artery (the aorta) and in the arteries in the neck just below the base of the skull (see Figure 2).

Placing the fingers on the peripheral arteries allows us to feel the pulse, or the rhythm of the heart beat. When the pulse pressure is reduced or the mean blood pressure drops, a flurry of neural signalling occurs. First, the intensity of nerve signals from the arterial pressure sensors to the central nervous system decreases. In response, the cardiovascular centre in the brainstem communicates back to the heart through the vagus nerve, which is responsible for heart rate among other things. The function of the vagus nerve is to restrain the nervous activity in the heart, to “put on the brakes.” In this case, the message from the brain orders the vagus to release the brake, thereby increasing heart rate and simultaneously unleashing activity in the sympathetic nerves.

If the vagus nerve acts as the brake, the sympathetic nerves act as the accelerator. They strengthen each cardiac contraction and constrict the small arterial resistance vessels throughout the body. When stimulated, these nerves help the body to counter stress by increasing heart rate and decreasing blood flow to the skin, muscles and gastrointestinal organs.

This reflex system functions quickly to keep blood pressure within strict limits around a given mean pressure, which is primarily set by the amount of fluid in the body and thus blood in circulation. The kidneys, then, play a dominant role in long-term blood pressure regulation because they regulate body fluid volume by filtering and excreting water and minerals, provided that intake of salt and water is not restricted.

**Decreased Gravitational Stress**

To understand how the stress of gravity affects blood pressure in humans, controlled, long-term bedrest is a useful investigational model to study what happens when that stress is reduced. If gravity does stress the cardiovascular system and increases blood pressure, one would expect that a long-term decrease in gravitational stress would decrease it.

There are indications that this theory holds true. Seven healthy men consented to six weeks of bedrest, where the beds were tilted head down at a 6º angle to simulate the fluid shifts experienced under weightless conditions (see Figure 3). During the experiment, mean blood
Looking up: Europe's quiet revolution in microgravity research

Pressure at heart level decreased during the day compared with a control period of normal bodily activity before and after bedrest. Interestingly, the hypotensive effect was maintained at the same level from the first week of bedrest until the 38th day. Thus, giving the body periods of reprieve from holding itself erect leads to lower blood pressure than that seen when the body normally remains upright. Researchers also observed that the output of blood from the heart seemed almost unchanged; so they deduced that this decrease in blood pressure was primarily caused by dilation of the smaller blood vessels, decreasing the resistance against which the heart pumps.

So can we blame high blood pressure on good posture? Maybe not, but these observations indicate that the daily stress of gravity does raise blood pressure. Gravity thus participates to some degree in setting blood pressure at heart level in humans.

Weightless equals stress-less

The weightless conditions in space offer a unique chance to observe how gravity modulates human physiology because gravitational stress is totally abolished. During simulation experiments on the ground, the gravitational load can be minimized but not nullified. Head-down bedrest can decrease the effects of gravity, but the gravitational force still affects the body from front to back, back to front, or side to side. Thus, in the end, there is no equal for actual weightless conditions to explore how the everyday effects of gravity affect the human body.

Thanks to a portable system worn by 12 astronauts, researchers were able to measure blood pressure for 24 hours during which the astronauts carried out their normal activities. Twenty-four-hour blood pressure measurements are used regularly in clinical work to establish whether an individual exhibits high blood pressure because blood pressure readings taken during daily activities are a more reliable predictor for development of cardiovascular disease than those taken during a few visits to a doctor’s surgery.

As a control, 24-hour measurements were recorded both before and after the flight while the astronauts were on the ground. Experimental measurements were taken under weightless conditions during missions that varied from five to 10 days. One set of measurements was performed on the first or second day of flight and another during the last.

The investigators observed a reduction in daytime heart rate as well as the diastolic pressure, the lower value in a blood pressure reading that indicates the pressure between heartbeats when the heart is filling with blood. The decrease in diastolic pressure was small but indicated that some degree of dilation of the small arterial vessels had occurred, and led the authors to conclude that spaceflight decreases the stress on the human cardiovascular system.

Cardiac output

While the 24-hour monitor allowed investigators to record what happened, it does not explain how. To find out whether a change in blood pressure is induced by a change in the output of blood by the heart or by dilation of the peripheral arteries, one needs to measure cardiac output.

Cardiac output can be measured using a closed breathing system, whereby the subject inhales and exhales a gas mixture to and from a rubber bag (see Figure 4). This gas mixture contains a tracer that is taken up by the blood flowing through the lungs. The amount of tracer remaining in the exhaled air is monitored. The rate of uptake is proportional to the amount of blood flowing through the lungs, which is the same as cardiac output.

When this method was first used in space, the rate of tracer uptake increased by some 18% during the initial days compared with the upright standing position on the ground, indicating a corresponding increase in cardiac output. This initial increase subsided a bit during the following days; however, blood pressure was not measured during this first investigation.
Because cardiac output increased in weightless conditions and blood pressure was unchanged or slightly reduced, the small arterial resistance vessels must have been dilated, because otherwise, blood pressure would have increased. We estimated a 14% decrease in resistance of the arterial vessels during a week of spaceflight as calculated by mean blood pressure divided by cardiac output, where the increase in cardiac output was 22% and the mean blood pressure remained unchanged (see Figure 5). The values in space were compared with values obtained on Earth while the subjects were sitting upright. Relatively speaking, a week in space is relaxing to the cardiovascular system.

**Confounding Kidneys**

When studying the reaction of an interconnected system such as circulation to an extreme change in environment such as weightlessness, however, the answer is never as simple as the adjustment of a single variable. The explanation for the body’s reaction is a complicated one, and in some respects appears contradictory. Observations made approximately 15 years ago indicated that the sympathetic nervous system is stimulated during space travel. As discussed previously, the sympathetic nerves are the “accelerators,” and their activity would be inconsistent with the relaxed cardiac state indicated by dilated blood vessels and decreased blood pressure.

This discrepancy becomes apparent when we examine the kidney and hormonal responses. During a Spacelab mission in 1993, four of the astronauts performed the first and, until today, only intravenous saline infusion during a spaceflight. The intention was to investigate how the renal output of salt and fluid would be affected by a week in space. Surprisingly, the rate of salt and urine excretion in space was significantly less than when laying prone on Earth and was at the same level as when sitting upright. In addition, levels of noradrenaline, a hormone transmitter of the sympathetic nervous system, not only increase in space, at times they are even higher than when a person is seated upright on the ground. Increased blood levels of noradrenaline were also observed later by other investigators during the Neurolab Mission that flew in 1998.

What makes these findings surprising is that usually, in a resting person, reduced excretion of salt and fluid and an increased noradrenaline concentration in the blood go hand in hand with
an increased peripheral vascular resistance—rather than the decreased resistance seen in space conditions. Conversely, an increase in cardiac output during resting, non-exercising conditions would be accompanied by less sympathetic nervous activity, meaning increased excretion of salt and fluids and decreased release of noradrenaline into the bloodstream.

**Lung–Heart Interaction**

One explanation for the above discrepancy could reside in the unique lung–heart interaction seen in weightless conditions, which is impossible to replicate on the ground. Without the pull of gravity, the thoracic cage expands, pulling the lungs and structures surrounding the heart open like an accordion, thereby further expanding the central vessels and the heart itself. This mechanical expansion of the thoracic cage is maintained throughout spaceflight, irrespective of its duration, and thus contributes to the increase in blood flow to the heart.

This reaction occurs during all weightless or near-weightless conditions—including parabolic, free-fall trajectory aircraft flights where weightlessness can be created for only 20–25 seconds. In these flights, the aircraft follows the same path as an object in free-fall, such as a cannonball fired into the air. During this brief time, we have shown that cardiac output increases by as much as 29%, and the arterial resistance vessels dilate, which leads to a decrease in blood pressure.

One hypothesis could be that thorax expansion stimulates the blood pressure responses in an unusual way so that sympathetic nervous activity is gradually stimulated instead of being suppressed. The continuous stretch of the vessels could cause a decrease in sensitivity of the chest cavity pressure sensors. Alternatively, the decreased extracellular fluid volume in the legs might also trigger sympathetic activity.

For now, however, these explanations remain speculative. We cannot explain the mechanisms for the body to be, physiologically speaking, both relaxed and agitated at the same time, but finding such an explanation is a high priority. We are currently monitoring blood pressure and cardiac output over 24 hours in astronauts during missions on the ISS of at least

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**ABOUT THE AUTHORS**

**Peter Norsk** is a professor in gravitational and space physiology at the department of Biomedical Sciences at the University of Copenhagen, Denmark. The purpose of his research is to understand how gravity affects blood pressure and volume regulation in humans, and whether it is a factor in the development of hypertension. For this purpose, chronic long-term weightlessness in space is a unique experimental model. Understanding how blood pressure is regulated is important for treatment of hypertension, which is the leading cause of death among the world’s population.

**John M. Karemaker** is an associate professor of Physiology at the Academic Medical Centre of the University of Amsterdam in The Netherlands. His interest in space research is directly related to his research in blood pressure control. Astronauts are the most healthy and most often medically tested subjects that one can imagine. Still, when returning from space they very often experience spells of dizziness or outright fainting. This condition is an important subject of research in the AMC, since “normal people” may also be plagued by this condition, which is very difficult to treat. It is his hope that the combination of both areas of research, space and terrestrial, may benefit both astronauts and patients alike.

**Lessons from the Animal Kingdom**

In fish, blood pressure must remain low because their one-chamber heart pumps blood through the gills before it can flow to the organs. Any substantial increase in blood pressure and they would bleed to death through the delicate structures of the gills. The arteries supplying the gills must therefore respond strongly and quickly to high blood pressure by slowing the heart beat.

Humans too have delicate structures, such as our lungs and brain, that cannot tolerate too high a pressure. In fact, the blood pressure in human lungs is about the same as that in a fish. The arteries that in fish supply the gills with blood have developed through evolution into similar sites in mammals (and thus humans), where systemic and pulmonary blood pressure is sensed.

Giraffes too can teach us something about pressure—and gravity. When compared with humans, giraffes exhibit much higher blood pressures at heart level, but exhibit similar blood pressures in the arteries just below the brain. This discrepancy indicates that the heart compensates for the varying distance between the head and the heart. Does that mean tall people are at risk for higher blood pressures than shorter individuals? That has not been determined, but there are indications that this is the case.
three months. Simultaneously, we are collecting blood to measure the noradrenaline concentration in platelets as a reflection of the long-term effects of weightless conditions on sympathetic nervous activity.

Perspectives

Hypertension. On the ground, people normally spend most of their time upright, and, as we have discussed, gravity takes its toll on a body continually in this position. When upright, blood pressure is higher in the lower portions of the body, which can induce constriction and structural thickening of the vessel walls of the dependent arteries and thus might contribute to hypertension and cardiovascular disease. The extent of gravity’s role in disease development and the potential ramifications of its removal are not clear.

Current data indicate that spaceflight may have positive effects on the circulation because the small arteries are continuously dilated, and the uneven pressure levels between the upper and lower body are abolished. However, investigations of the heart muscle in space have produced conflicting results. One report showed that the ability of the heart to contract was compromised immediately after 129–144 days of spaceflight. In contrast, Russian scientists used ultrasound to perform cardiac scans of 15 cosmonauts following a few months of spaceflight and concluded that the pumping of blood from the left heart chamber was improved.

Clearly the health of the astronauts demands that we find a definitive answer for these conflicting results. We are currently exploring the effects on the cardiovascular system of extended missions of six months on the ISS. Preliminary results indicate that the increase in cardiac output and dilation of peripheral arterial vessels continues during these missions of several months. If confirmed, these results could mean that spaceflight and weightlessness over long periods of time are healthy for the cardiovascular system.

Heart failure. Data from space and simulation studies also have implications for understanding how gravity stresses patients with heart failure. In heart failure, the pumping capacity of the heart is reduced and thus is more sensitive to the pull of gravity. The insufficient pumping of the blood through the kidneys activates the hormone system that helps regulate long-term blood pressure, leading to constriction of the blood vessels and fluid accumulation in the body.

To alleviate the stress of gravity in heart failure, we have immersed patients in thermo-neutral water of 34.5°C. Here, the outside water pressure compensates for the gravity-induced pressure gradients in circulation, which leaves the cardiovascular system virtually weightless. When we compared study parameters in these patients with control patients sitting upright, water immersion improved the circulatory condition in the heart failure patients, who had been stabilized with standard medical drug treatment prior to the intervention.

Because the results seen during spaceflight validate those seen during water immersion, it is fair to conclude that gravity is a constant burden for heart failure patients, which aggravates the condition. Further development and study of situations that alleviate the stress of gravity may lead to future therapies for these patients.
Clinical Immunology in New Frontiers

When thinking big, we must also remember to think small, especially when we need to fend off illness in space. As Victor Hugo once said, “Where the telescope ends, the microscope begins; and who can say which has the wider vision?”

By Alexander Choukèr, Boris Morukov and Clarence Sams

Before 1961, when Soviet cosmonaut Yuri Gagarin became the first human in space, many considered our very survival in such circumstances to be impossible. Debates erupted about whether there would be fatal incidents of heart failure. No one knew what would happen to the body in the absence of gravity. At no stage had the evolutionary process prepared human beings to live without it, in isolation and darkness and in an overall hostile environment.

Since that historic voyage, people have continued to push the boundaries of space exploration and have survived the experience in increasing numbers. With the ensuing progress of technology for international spaceflight, two or more cosmonauts/astronauts were routinely sent to space during the Soviet Salyut and Mir missions and the US Gemini/Apollo and Space Shuttle missions. While the concerns of fatal heart failure proved, thankfully, to be unnecessary, physiological changes as a result of space travel did occur in other areas.

Blood analysed from astronauts after the 1973 NASA Skylab Mission showed that immune function was altered. More than 50% of the Apollo astronauts had experienced either bacterial or viral infection during spaceflight and then later upon return to Earth. Although most prominent research of human life sciences in space is usually focused in areas such as bone and muscle loss, these results inspired more profound investigations in the field of fundamental immunology. Maintaining good health under the unique stresses of space travel requires intense study of the immune system. After all, the nearest hospital is hundreds of miles

AT A GLANCE

- Many factors contribute to immune system suppression in space, including lack of gravity, cosmic radiation and highly stressful living conditions.
- Blood analyses have shown that both the innate and adaptive arms of the immune system are negatively affected by microgravity, and confinement studies have shown inhibition in response to stress.
- Current study is focused on using small monitoring devices to watch for how and when immune changes become a health risk to better target prevention and therapy.

—The Editors
away. Research into the body’s reaction to microgravity and cosmic radiation, as well as the psychological stress of living in a hostile environment, is crucial before attempting longer missions to Mars and beyond.

**Lines of Defence**

In broad terms, the immune system consists of layered mechanisms that protect the body from disease. Containing a wide variety of cell types, if you were to add up its more than four trillion cells, the human immune system weighs more than the liver and brain put together. The first lines of defence are those surface barriers between the host and its environment, including physical barriers such as skin and mucus as well as chemical barriers such as stomach acid and enzymes in saliva or tears.

Invading microbes that penetrate the surface and enter the host body meet the second line of defence—the so-called “innate” immune system—that includes phagocytes, white blood cells that engulf and destroy pathogenic (disease-causing) bacteria, virus-infected cells and other foreign substances. This second line of defence is located in tissues such as the lung or intestine, which can be vulnerable entry points for germs. When under attack, the innate system triggers a generalized inflammatory response, which causes redness and swelling as well as the fever and body aches associated with the flu. When this system overreacts, the aberrant inflammation can damage cells and tissues, causing significant clinical problems.

This inflammatory response can be initiated by a vast re-circulating pool of innate immune cells in the blood or tissues that act through important and evolutionarily preserved receptors on cell surfaces, the toll-like receptor family. These receptors control the production of signalling proteins called cytokines that induce inflammation and activate immune cells in response to invading microbes. These immune cells are located in more than 500 lymph nodes throughout the human body, waiting inside like military troops on active reserve. Lymph nodes

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**FIGURE 1. INNATE IMMUNE CHANGES IN SPACEFLIGHT**

In the course of fighting bacteria, killer white blood cells called phagocytes (which in Greek means “cell-eater”) produce hydrogen peroxide ($H_2O_2$). In this study, blood was taken from astronauts and an immune reaction induced using either an ion-carrier with antibacterial properties (A23187) or an organic compound used in research because it promotes tumor growth (PMA). Blood was tested before spaceflight and then again one and seven days after return from a six-month mission. The Y-axis shows the signal intensity of $H_2O_2$ production, and the X-axis defines the population of white blood cells (granulocytes) when scanned through a laser beam (FSC = forward scatter).

**A23187 RESULTS** (left): The rate of $H_2O_2$ production was reduced by more than half on the first and seventh days after 6 months in orbit compared with normal preflight rates of about 700 units.

**PMA RESULTS** (right): In contrast to the ion carrier results, the capability to generate adequate $H_2O_2$ did not change after spaceflight when stimulated by PMA, which may indicate that cell functions can be restored.
act as sentries along the castle walls: they detect the presence of invaders, process the threat and sound the alarm. The troops are released and when they recognize a pathogen, they trigger the cytokines that unleash both the general inflammation described above and a more specific, or adaptive, response described below.

This generalized innate immunity is an ancient defense system found in orders of life from fungi to plants to starfish. Only higher vertebrates like humans developed a third line of defense that reacts specifically to the germ itself. After the first exposure to a microorganism, “killer” B- and T-lymphocytes are able to recognize that microorganism so that on the second encounter, the response is targeted to that specific germ, allowing more rapid and more efficient action and elimination.

In their lifetime, lymphocytes may or may not encounter the target they are capable of recognizing, but if they do they can be activated to multiply into a large number of identical cells. T-cells recognize the invaders by their specific proteins or antigens and can either directly attack the invaders or activate fellow T- or B-cells. The B-cells produce antibodies that either help destroy the microorganisms or mark them for attack. Adaptive immunity is the principle behind the efficacy of vaccination and the acquired immunity from diseases such as chicken pox that occur once, most often in childhood.

**Immunity Altered by Stress**

Germs and microorganisms are not the only threats that provoke the immune system to leap into action. Environmental or situational change can tax the body in other ways, creating a physical response. Although the definition of “stress” is still a matter of debate in this context, stress research pioneer, endocrinologist Hans Selye, succinctly defined the adaptation processes of any biological system to environmental changes:

“Stress is a non-specific response of the body to any demand placed upon it … [it] results whenever we are faced with external changes or demands and such demands include any variations in the individuals’ environment.”

In general terms, stress is a challenge: can we adapt to a new condition, regardless of what it may be, as quickly and with the least damage to ourselves as possible? Sweating is a simple example: faced with a rise in temperature, we sweat to cool off and maintain a constant temperature.

**FIGURE 2. ADAPTIVE IMMUNE CHANGES IN SPACEFLIGHT**

T-lymphocytes can remember a microbe after the first exposure, a property called adaptive immunity. As part of this function, T-lymphocytes produce chemicals called cytokines that aid in the immune response. Two cytokines were measured in this study: interleukin 2, which stimulates growth and differentiation of T-cells, and interferon-y, which inhibits viral replication among other functions.

Human T-cells were separated and grown in culture medium that induces cell reproduction. Preflight results showed normal production of interferon-y (green circle) and interleukin-2 (orange circle). After a long mission on the ISS, T-cells were almost completely unable to generate both cytokine messengers.

**ABOUT THE AUTHORS**

Alexander Choukèr attended medical school at the Ludwig-Maximilians-University (LMU) in Munich, Germany. He completed scientific training at the LMU and at the NIH in Bethesda, Maryland, US. Currently he is based in the Department of Anaesthesiology at the LMU and is associate professor and clinical specialist in Anaesthesiology, Intensive Care and Emergency Medicine at the LMU’s medical faculty. In 2003, he was awarded the John E. Fogarty fellowship grant from NIAID at the NIH. In 2007, he received the Berblinger Award by the German Academy of Aviation Medicine. Since 2007, he has been vice chairman of the ESA Life Sciences Advisory Group (LSAG) and coordinator of the ESA topical team on immunology.

Boris Morukov attended medical school at the Second Moscow Medical Institute in Moscow and received a PhD in space, aviation and naval medicine from the Institute for Biomedical Problems in Moscow, Russia. He completed scientific training as a cosmonaut/researcher and as a flight surgeon at Johnson Space Centre in Houston, Texas, US. Currently he is deputy director and head of Department of Biochemistry and Immunology at the State Research Centre RF-Institute for Biomedical Problems of the Russian Academy of Sciences.

Clarence F. Sams received his PhD in 1983 in biochemistry from Rice University in Houston, Texas, US, and performed postdoctoral research at the University of California, Berkeley. Dr. Sams served as project scientist for NASA, and is currently the director and technical monitor of the Immunology Laboratory at Johnson Space Centre in Houston. Dr. Sams was awarded the NASA Exceptional Service Medal in 1998. In addition to his research activities, Dr. Sams currently serves as project scientist for the ISS Medical Project, which integrates flight-related human life science research on the ISS.
The immune response is obviously much more complicated. This system is not autonomous and several co-factors affect responses when adapting to a stressful, new environment. Space missions demand that humans cope with living conditions never experienced before: primarily the absence of gravity plus varying degrees of cosmic radiation. In addition, astronauts face mental stress that results from confinement and uncomfortable and unnatural living and working conditions including the lack of privacy, a heavy workload and an abnormal day–night cycle. In addition, the microbiological environment on the space station changes over time and germs may evolve in response.

**Effects of Microgravity**

Depression of T-cell lymphocyte activation due to near-zero gravity was first observed in an experiment conducted during the Spacelab 1 Mission in 1983. The data triggered several other investigations that attempted to map the complex mechanisms of T-cell activation and suppression both in space under true microgravity and on the ground in the clinostat machine, which is used to approximate microgravity.

Results showed that these effects and the potential consequences to our ability to fight off germs were indeed debilitating. The lymphocytes exposed to microgravity almost completely lost their capability to react in their normal defensive role. Studies of animals conducted in space also indicated reduced killer cell activities and a higher susceptibility to viral infections.

This suppression is thought to happen because the organization of the cells is geared to gravity; without it, the cells become disoriented and fail to function normally. Cell architecture consists of a cytoskeleton, which functions like scaffolding. It maintains cell shape as well as plays an important role in intracellular transport and communication. Recently it has been shown that microgravity alters certain internal signalling pathways of immune cells, thus causing those cells to function improperly.

**Cosmic Radiation**

Cosmic radiation is everywhere in space. When combined with other stress factors such as microgravity, it is highly likely that radiation can have an aggravated effect on the immune system.

When on extended missions, astronauts will be exposed to stronger and more varied types of radiation than that experienced normally. These radiation types consist primarily of solar energetic particles, protons and highly charged energetic particles of galactic cosmic rays. The degree of exposure to solar energetic particles will increase during interplanetary missions as the partial “shielding” that results from the Earth’s magnetic field is left behind when leaving Earth’s orbit.

Although little is known about the consequences of cosmic radiation on immune cells, many publications confirm the impact of other forms of radiation on immune cells. Such radiation can kill cells, cause mutations, cause inflammation and malignancies and otherwise weaken the immune system and induce immune system disorders and cancer. This damage, however, can take years to become apparent. So while an astronaut returning home from a long mission may appear to be healthy, is there a time bomb ticking away somewhere within the body?

**Mission-Associated Stress**

Like that of cosmic radiation, the consequences of mission-associated or mental stress are insidious and may not be immediately apparent. In addition, we may not immediately associate stress with an immune system response. Conditions such as post-traumatic stress disorder are often associated more concretely with psychological trauma than with long-term physical problems, as there is little conclusive research in that area. To understand the relationship between the mind and the immune system, we must first consider the human body as a whole, with complex, interrelated systems. Immune system function depends on the informational signalling of both the endocrine and nervous systems.

The endocrine system is composed of small organs that produce hormones, chemicals that act as messengers to regulate not only immunity but metabolism, growth, puberty and other “holistic” or whole-body functions. These hor-
Hormones circulate in the blood from their place of release to their target cells, tissues and organs. These hormones can be produced and act locally or be produced by a distinct gland such as the pituitary, thyroid or adrenal gland and transported through the blood to the active defence cells. Once there, the hormones will stimulate, inhibit or maintain cell function depending on the messages sent.

During extended periods of stress, our defences are kept on alert. Cortisol, a glucocorticoid that is often referred to as the “stress hormone,” circulates at higher levels in response to stress and other potential dangers. It increases blood pressure, blood sugar levels and suppresses the immune response. Cortisol and other hormones are released into the blood in response to neural stimulus and their levels are controlled by brain activity.

Investigating Stress
While the physical processes behind the effects of stress on the body are complex, the real-life translation can be unfortunately simple. When under strain, we are more likely to get sick. In studies of medical students during the highly stressful time of exams, tests showed increased stress hormones and suppressed immune cell activities, which resulted in the reactivation of dormant herpes simplex virus type 1 (cold sores) as well as the Epstein-Barr virus. Other investigations showed that psychological stress can affect wound healing and responses to vaccination, supporting the hypothesis that stress does negatively affect immune responses with potential clinical consequences. Clinical investigations have shown that patients under psychological or mental stress also exhibit signs of impaired and altered immunity.

Other investigations have been conducted of stressful living conditions, an important concern for astronauts. Earth-bound confinement studies have illustrated the effects of this type of stress on regulation of the immune system. The extreme living conditions studied were similar to those experienced during spaceflight. In different studies, subjects either were confined for 10 to 240 days in modular chambers that mimicked the living quarters in space or were confined in isolation for months in the Canadian Arctic. The stress responses and specific immune changes seen in these studies were quite similar to those observed in astronauts after spaceflight.

As with the medical students, confined sub-

Clinical immunology is the study of diseases caused by disorders of the immune system (failure, aberrant action and malignant growth of the cellular elements of the system) as well as diseases of other systems where immune reactions play a part in the pathology and clinical features. The results of blood tests from the 1973 NASA Skylab mission were a wake-up call for the field. The astronauts’ immune functions were clearly altered following spaceflight. Afterward, the resulting investigations first used in vitro cell suspensions containing lymphocytes, a type of white blood cell, to estimate the effects of gravitational changes on specific immune cell responses. Emerging methodology in biomedicine has allowed immunologists to further study relationships between the organ systems and the immune responses. In addition to controlling infections and eliminating germs, immunologic responses are also responsible for eliminating non-functional or dysfunctional tissue cells (e.g., tumor cells). Failure to maintain adequate immunity may result in autoimmune diseases (e.g., rheumatoid arthritis), acute and life-threatening infections, overwhelming systemic immune responses (e.g., septicemia) or the development of cancer.

Psychoneuroimmunology (PNI) is the field of human physiology research dealing with the complex interactions between the central nervous system, endocrine and immune systems under conditions of stress. PNI researcher Kevin Tracey from the Feinstein Institute for Medical Research in Manhasset, New York, and Ronald Glaser from The Ohio State University Mind/Body Center in Columbus, Ohio, have shown that brain activity and the nervous system control inflammation in a feedback manner where hormones are released into the blood in response to a neural stimulus, altogether affecting immune and health status.
jects showed a reactivation of the herpes virus, which is usually dormant in healthy adults. This virus also became active during spaceflight. Under these conditions, the body’s ability to respond to a threat such as the herpes virus decreases. Stress causes cortisol to be released and suppress immune functions of both the innate and adaptive systems by inhibiting cytokines and T-cell production. After missions of several months, samples of the astronauts’ blood illustrated that the immune cell functions of both the innate and adaptive immunity were indeed suppressed in the first days after return to Earth (see Figures 1–3).

These tests and subsequent experiments also revealed higher levels of catecholamines circulating in the astronauts’ blood than in non-stressed subjects. Like glucocorticoids, catecholamines are chemicals released by the adrenal glands. Although the glucocorticoid stress response is more well known, catecholamines suppress the cell activation pattern of white blood cells. The most recognizable catecholamine is epinephrine, commonly known as adrenaline. Along with norepinephrine, these “fight-or-flight” hormones not only increase heart rate and blood pressure but also inhibit immune cells’ capability to ingest microbes.

**Hidden Threats**

How will an already suppressed immune system cope with challenges from the microbiological environment in a closed space station or a remote habitat? Although no unusual microbial hazards have been indentified to date, the International Space Station will inevitably house an unknown number of microorganisms that will increase with the duration of operation. Recent surveys have identified some potentially opportunistic pathogens, and the number and types of microorganisms may further increase with the length and number of missions and the number of visitors to the ISS.

Not only is the microbiological load itself subject to changes, but the bugs’ ability to cause disease are also subject to change during spaceflight. In fact, the virulence of specific bacteria has been shown to intensify. Researchers tested this by growing the bacteria *Salmonella typhimurium* on board the space shuttle and comparing this growth with ground control cultures. Complex proteomic and genetic analyses revealed that changes in gene transcription and protein synthesis resulted from spaceflight. These changes were not only of interest for “academic” reasons but also because these bacteria increased infection in a mouse model. In summary, the variable microbiological environment together with the greater disease-causing ability of bacteria may increase health risks to the astronauts when the suppressed immune system is confronted with microbiological contamination.

**An Ounce of Prevention**

Systematic investigation of the human immune system’s adaptation in space has recently begun on the ISS. Current scientific projects include Immuno and Integrated Immune. The upgraded research opportunities available on the ISS Columbus module will enable more intense investigations into the interaction of the human immune system with the specific microbiological environment on the ISS.

In addition, Earth-bound studies of controlled bedrest, confinement in the Arctic or Ant-
A journey to Mars and back was once thought possible, but the challenges to define and develop suitable living conditions for such a mission are complex and still poorly investigated. In addition, the loss of visual contact with Earth or “Earth out of sight syndrome,” during such a long mission and the communication delay that will surely occur will add new mission-associated stress.

**Beyond the ISS**
A journey to Mars and back was once thought to be the realm of science fiction, but explorations of this kind are being actively discussed by scientists and engineers today (see “Mars500,” opposite page). These plans could become reality in our children’s lifetime, and one of the most crucial requirements will be adequate life support systems and living conditions.

Even with that issue addressed, however, the conditions on lunar or Martian surfaces and their consequences on human immunology are poorly investigated so far. In addition, the loss of visual contact with Earth or “Earth out of sight syndrome,” during such a long mission and the communication delay that will surely occur will add new mission-associated stress.

Any exploration of Mars and, looking even further into the future, lunar or Martian colonization program means facing technical challenges to define and develop suitable living conditions. Creating a robust habitat with the atmospheric pressure that the human body is accustomed to on Earth requires an enormous amount of energy. Finding the lowest acceptable value of continuous atmospheric pressure that the body can tolerate will be critical to the efficient running of a life support system. If the atmospheric pressure and oxygen levels are too low, the oxygen deprivation would result in a condition called hypoxia similar to that seen in climbers with altitude sickness. A subnormal oxygen level in tissues leads to symptoms that include headaches, shortness of breath and nausea. The effects of prolonged hypoxia on immune cells could result in immune suppression as well as other challenges to the system.

**Summary**
In recent years the scientific community became aware that the combination of multiple sources of both physical and mental stress that occur during spaceflight can have detrimental effects on the immune system. Understanding how this system will cope with the even greater stress of extended duration missions such as interplanetary spaceflight is absolutely essential to reduce the risk to those brave enough to crew such a mission.

An international research approach will open new insight into the regulation of immune responses and will address health concerns that may occur during these missions. In the newly installed Columbus research laboratory and other modules of the ISS, researchers will use a multidisciplinary approach to understand better how microgravity, cosmic radiation and mission associated stress can influence immune function. In addition to the crucial task of maintaining the astronaut’s health, this research will also benefit patients here on Earth with the potential for targeted drug treatment, vaccinations and other therapies. These achievements could be implemented into the treatment of any patient, of any age, at any location, from the local clinic to the ISS.

**ACKNOWLEDGMENTS**

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SPECIAL REPORT:

Bone Loss
in Space

During the many millions of years in which vertebrate animals evolved, the human skeleton gradually stood erect, against the Earth’s gravity. As part and parcel of this feat, the skeletal system also evolved to function within its boundaries—to withstand its force and the impacts caused by simple movements like walking. The skeleton’s primary role is locomotion: it allows the body’s muscles to move the limbs. Secondary roles such as maintaining balance and supporting the body’s shape are influenced by the demands of movement. Bone cells adapt to these variables—the total mechanical load or stress placed on them—for more efficient performance.

Despite its inflexible appearance, bone is a living tissue, and it must continually destroy and rebuild itself throughout a lifetime of use. This process, called remodelling or turnover, occurs in two phases. The rapid resorption phase takes two to three weeks and then the slower formation phase lasts two to three months. Different types of bone cells carry out these phases. Osteoclasts degrade the bone surface and release calcium to be reabsorbed. Osteoblasts then fill in the pit with new bone.

Bone tissue works to increase or decrease skeletal mass based on its use. This means that during times of increased exercise, for example, skeletal mass is preserved or increased. Conversely, it decreases with reduced exercise or movement, which is what happens to astronauts during spaceflight.

Simply put, the skeleton doesn’t have to work as hard without the pressure of gravity. In near-weightlessness, not only is less movement required and fewer impacts felt but less strength and power is required to execute the motion. The detrimental effects of this extreme “unloading” on astronauts have been seen since the earliest spaceflights. Experiments have carefully documented bone loss in various parts of the body and in different types of bone tissue, but research continues into exactly how and why these losses occur. Part of this research is focused on the bone cells themselves and their ability to “sense” the mechanical load placed on them in order to adapt to it. How gravity and other loading factors are detected and then translated into a response is yet unknown.

Because of this long history of intense research, two articles are presented here that examine the effects of microgravity from very different angles. The first article, “Zero Gravity: Bad to the Bones,” by Laurence Vico and Christian Alexandre, reviews evidence of bone loss during missions from the 1960s to today. Results from these studies show markers of increased resorption, overall calcium losses, and a gradient of loss that increases beginning at the spine through the lower body. The authors also analyse data on whether losses occurred in the hard outer layer of bone or the more porous bone interior.

The second article, “Our Sensitive Skeleton,” by Rommel Bacbac, Jack van Loon and Jenneke Klein-Nulend, looks at bone adaptation on the cellular level. The authors discuss what is known and unknown about how bone cells called osteocytes sense gravity and mechanical stress. They also analyse the high level of sensitivity of bone cells to minute amounts of strain as well as the effects of different types of strain or stress on bone formation.

How this knowledge translates into prevention and recovery is the ultimate goal. Current strategies to counteract microgravity’s effects consist mainly of exercise, but it has not been enough.

Sticks and stones may break your bones, but underuse will make them brittle. Like extended bedrest, an environment without gravity reduces the workload on bones and makes them weaker. Because research in this area is extensive, two articles are presented here to illustrate different approaches being taken to understand—and combat—these effects.

As we explore further out into space, astronauts will have to spend more time in microgravity and risk increasing losses in bone density. Some research indicates that the rate of recovery for missions of several months can exceed twice the time spent in space, but no one knows how or if the body would recover after spending years there. Research into the dynamics of skeletal changes, cellular communication and how to effectively increase the mechanical load on bones is necessary not only to protect the health of the astronauts but also to combat osteoporosis here on Earth.
AT A GLANCE

■ Bone loss in space seems to occur in a gradient that begins at the spine and becomes greater in the lower limbs.
■ The rate of recovery after long missions can exceed twice the time spent in microgravity conditions.
■ Future study should focus on the dynamics of bone loss, its relationship to other body systems and more effective exercise and/or prevention strategies.

—The Editors

A

fter early explorations into space when doctors announced that the astronauts had suffered bone loss, people all over the world took notice. For many, “bone loss” spelled “osteoporosis,” a disease associated with aging; not with the strong, robust young men who were sent into space. Literally translated to mean “porous bones,” osteoporosis is a common aging disorder that affects a large portion of older people. The World Health Organization estimates that the condition is responsible for approximately 650,000 fractures a year in the European Union alone. In fact, one WHO report states, “Osteoporosis-induced fractures cause a great burden to society,” and adds that such hip fractures can affect 40% of women over 50 years old.

While hormonal and other changes associated with aging are the main considerations for osteoporosis on Earth, in space, lack of gravity results in reduced mechanical use of bones. Both the decrease in strength or power necessary to create movement and the decrease in the amount of movement overall are thought to be the main factors leading to bone loss in astronauts. Studies have shown that the number and the amplitude of various demands on the skeleton while in orbit are extremely low compared to the numerous impacts during daily life on Earth. In fact, near weightlessness reduces the stimuli on bone by approximately half of that experienced during a typical work day on Earth.

Little wonder then that doctors and scientists saw a two-pronged reason for delving further into the cause and effect of bone loss in space. The first was to prevent the foreseen danger to astronauts’ health during long, interplanetary missions, and the second was to find new ways to combat such a widely experienced condition on Earth. In addition, the microgravity environment also offers the means to study other factors that are either difficult to observe and measure on Earth or have not yet been investigated.

Early Indications

Two important parameters have marked the increasing level and speed of research. First, as the length of missions increased, researchers were able to gather more useful data. Second, the means to gather data improved with the advent of more precise instruments.

After most of the early Gemini and Apollo missions in the 1960s, astronauts showed both increased urinary calcium levels and decreased bone mineral density (BMD) as measured by radiodensitometry. Urinary calcium is an indicator of bone remodelling, or turnover. As bone tissue rebuilds itself, it first destroys old bone and then replaces those cells with new bone. Cells called osteoclasts degrade bone tissue by secreting substances that dissolve calcium and other minerals that make up its structure, a process called resorption. An increase in urinary calcium can indicate a corresponding increase in bone resorption and release of calcium from bone into the bloodstream—in the absence of other factors such as increased calcium intake.

The Beginning of Long Flights

Beginning with the studies conducted during the three Skylab missions in the 1970s: Skylab 2 (29) days, Skylab 3 (59 days), and Skylab 4 (84 days), we could see greater bone loss in the heel compared with the upper limbs as a function of the time spent in microgravity. The astronauts’ urinary calcium output progressively increased to
Bone loss in astronauts was first documented in the early flights of the 1960s. Since then, longer missions and better equipment have enabled more detailed research and a wealth of data. 

By Laurence Vico and Christian Alexandre

80–100% above normal, where the levels eventually plateaued. In addition to calcium, other urinary markers of bone degradation increased: the amino acid hydroxyproline increased up to 33% and urinary phosphorus also increased. After the Skylab 3 and 4 missions, bone loss was found in the heel while no changes were observed in the two forearm bones.

Three months after the 84-day Skylab 4 flight, heel bone density was still significantly lower than normal. Frozen urinary samples recently analysed with specific blood tests developed to measure biochemical markers of bone remodeling confirmed the increased resorption.

Peace in Space
In 1986 the Soviet Union launched the first functional, operating space station. Named after the Russian term for peace or world, Mir not only provided a long-term crewed vehicle for experiments, it also allowed scientists to gather invaluable data on what was happening to the astronauts’ bodies during previously unexplored lengths of time during a mission.

After the fall of the Soviet regime, the Russian space agency, NASA and ESA were able to expand the use of Mir for collaborative missions. Flight times of up to 312 days, with periodic measurements, provided a general picture of what was happening, while allowing for individual metabolism, size and age of the astronauts. These studies indicated that bone and overall calcium loss resulted from a combination of reduced intestinal absorption of calcium, increased calcium excretion and increased bone resorption. Markers of bone formation decreased after 14 days of flight; but after 60 to 110 days of flight, levels were similar to pre-flight values. One consistent result seen across the different studies was an increased amount of bone formation markers after the flight, which indicates enhanced metabolic activity.

Although microscopic bone tissue samples of astronauts were never tested, these analyses were done in studies of the effects of bedrest on bone mass. Here, biopsies of the iliac crest (part of the pelvis) indicated reduced bone formation activity; however bone formation markers were not decreased. This seeming contradiction is an important reminder to consider and test both site-specific and systemic activity.

Bone Structure
Later missions incorporated more detailed study of how and where bone loss occurred within the structure of the bone itself. Bone consists of both compact and spongy tissue. Compact or cortical bone makes up the hard outer layer of bones, and spongy or trabecular bone, which is porous like a sponge to allow blood vessels and other cells to traverse the bone interior, makes up the inner cavity.
The first comprehensive documentation of bone loss by tissue type was taken from two cosmonauts who flew in one- and six-month missions, respectively, and was later confirmed on another 15 cosmonauts. In addition to peripheral quantitative computed tomography (pQCT) of the distal radius in the arm and the tibia in the leg, ultrasound measurement was performed on the heel bone. After the six-month flight, bone loss in the tibia and the heel was more marked than that seen after the one-month flight, whereas no loss was observed at all in the radius. Although no change was seen in the radius regardless of mission duration, BMD loss in spongy bone of the tibia was already present after the first month and continued to deteriorate with mission duration. Loss of cortical bone tissue in the tibia occurred after a two-month flight but was less pronounced than that for trabecular bone.

Later, in the year 2000, crew members on International Space Station missions were subject to BMD testing using QCT measurements of the hip and spine in addition to the routine dual energy X-ray absorptiometry (DXA) measurements. Before and after flight measurements conducted in 14 astronauts who performed four to six-month missions showed that they experienced substantial loss of both trabecular and cortical bone in the hip and somewhat smaller losses in the spine.

Viewing these results as a whole, it seems that there is a gradient of mineral loss beginning at the lumbar spine level and becoming progressively greater in the lower limbs, including the attachment point of the femur and distal tibia but excluding the heel. This progressive decline is also characterised by higher percentage loss of trabecular bone compared with cortical bone. The upper limbs appear to be protected from loss of bone minerals and there have even been surprising reports of increased BMD in the skull (see Figure 1). One reason may be that a redistribution of minerals from the lower to upper body occurs in space as gravity no longer exists to pull fluids to the lower extremities.

Another explanation for the absence of bone loss in the radius is that the arms play a greater role in locomotion and in overall movement in space than the legs. So while the lower limbs experience a decrease in use, the upper limbs experience an increase, which may contribute to the skeletal adaptation in both instances. Test results varied widely between individual astronauts and no relation with potential confounding factors, including previous time spent in space, was found. Measurements were also taken during a recovery period equal to the mission length. During recovery, bone loss persisted in the tibia; suggesting that the time needed to recover is longer than the mission duration.

**ABOUT THE AUTHORS**

Christian Alexandre was educated at the Medical School of Lyon, France. He is currently dean of the medical school and a practicing rheumatologist based at St-Etienne Hospital-University, where he specializes in bony diseases. While at St. Etienne, he developed the Inserm research laboratory dealing with bone adaptation to stressful conditions of intensive exercise and weightlessness.

Laurence Vico was educated in St-Etienne and Lyon Universities in France. She is the present director of Inserm research laboratory for the biology of bone tissue at St-Etienne School of Medicine.

Both C. Alexandre and L. Vico received the Philip Morris scientific award in 1992 in life sciences and space.
Confounding Factors

These reported losses in bone mass occurred despite physical exercise training. Although these changes have been mainly attributed to decreased body movement and reduced weight bearing, there are other associated factors that contribute to bone loss to unknown degrees. Magnetic resonance imaging (MRI) evaluation in 16 astronauts on four- to six-month missions showed that muscle volume did not change in the upper body but decreased in the back and legs, with the greatest change in the lower leg. These regional changes in muscle mass seem to mirror those of bone.

Researchers have attempted to associate this upper/lower body discrepancy with the aforementioned fluid redistribution caused by microgravity. The loss of gravity-induced pressure gradients in the lower body causes fluids to shift to the upper body. The kidneys, which are the primary regulators of body fluid volume and composition, respond to the fluid shift and bone demineralization by increasing the urinary output of water, sodium and calcium.

This increase in urine production and sodium excretion occurs soon after entering a microgravity environment and was thought to contribute to loss of astronauts’ body mass. However, continuous daily body mass measurements showed a gradual reduction over the entire mission instead of a rapid loss of 2 to 3 kg at the beginning of a mission. Studies of energy (caloric) intake versus energy expenditure have shown that astronauts are burning more calories than they are consuming, resulting in a negative energy balance and a loss in body mass. Insufficient vitamin K intake (to the best of our knowledge, fresh vegetables were scarce on the Mir space station) seems to also contribute to bone loss. During a 179-day mission, investigators administered 10 mg of vitamin K to one astronaut from day 86 to day 136. During and after being given the extra vitamin K, bone formation markers increased significantly. Other factors that

Stripped to the Bone

Throughout life, the body continuously destroys and rebuilds bone tissue, a process called remodelling. Two types of cells perform these functions: osteoclasts, the destroyers, and osteoblasts, the builders. Left: Osteoclasts invade the bone’s surface and release dissolving enzymes, which carve out pits in the bone and release calcium to be reabsorbed. Right: Osteoblasts then swarm into the pit and secrete calcium and proteins to fill it with new bone
may contribute to bone loss are disruption of circadian rhythms as well as neuromuscular and vestibular systems, but the potential impact on the skeleton have not yet been investigated.

**Rate of Recovery**

One year after ISS astronauts returned to Earth, bone mineral testing was again performed on the femur to assess the effects of reexposure to Earth’s gravity. Area and volumetric bone mineral density, bone volume, as well as bone mineral content (BMC) were evaluated. Results showed that BMC of the femur had recovered, but overall BMD results and estimated bone strength showed only partial recovery. The return of BMC to normal values can be attributed to an increase in bone volume and cross-sectional area while BMD remained below normal.

Additional research results indicate that recovery of skeletal density after long-duration space missions may exceed twice the time spent in microgravity conditions. These relatively long recovery periods may be due to the type of bone cells and mechanisms compensating for the overall loss. The outer layer of bone is the periosteum, and these cells regulate the general outer shape of bone, including length and thickness. Most periosteal expansion takes place during puberty when hormonal changes induce the growth spurt that determines our adult height among other things. Little periosteal growth occurs during advancing age when it serves to partially maintain the cross-sectional area of bone, so any periosteal compensation in an adult would take a significant amount of time. The extent to which this compensatory effect protects against fracture, however, remains to be seen.

Fracture is one of the key health risks of osteoporosis, one that usually occurs after the disease has quietly ravaged the body over time. While it will take years for fractures to occur, other symptoms related to fluid shifts are immediately observable when the astronauts return to Earth. Changes in volume and composition of fluids surrounding muscle cells can cause water retention in those cells, making them swell and become painful. The doctor for the French National Space Agency noted that returning astronauts experienced flat feet as well as back pains several days after returning from space. Tennis players also said that they systematically hit under the ball on the two or three days after landing.

**Future Steps**

To make a better assessment of microgravity’s impact on bone, the next research step is to establish the dynamics of skeletal changes during microgravity exposure as well as under different levels of microgravity. Obtaining a better understanding of these effects is especially important in view of the planned Lunar and Mars explorations, as these longer missions will require better prevention strategies. Evaluations of these dynamics require not only measurements of bone resorption and formation markers but also repeated assessments of site-specific changes during flight to bone volume, mineral content, density and so on.

Because of limited space, a miniaturized peripheral QCT was developed to measure trabecular and cortical BMD separately. This apparatus has now evolved into a high resolution device able to evaluate the three-dimensional structure of the skeleton (see Figure 2). A 3-D view will allow researchers to validate or refute whether bone resorption in space occurs equally in all planes of trabecular bone. Also unknown is whether the recovery of BMD is uniform or whether it is selective for the horizontal planes of bone.

**FIGURE 2. BONE STRUCTURE** Representative 3-D reconstruction of the tibia with peripheral QCT showing the distinct regions for volumetric BMD evaluation. All planes of bone are visible: the outer cortical area and the two trabecular regions of interest: the intermediate area and inner trabecular area.
or vertical spongy bones. These answers have important implications for future bone health and risk for potential fractures, especially of the vertebrae and hip. Even if bone density recovers, the 3-D structure of the bone may be altered, which could compromise its architectural integrity. In addition, most of the present data have been obtained in men. More data collection is needed not only in men but also in women because gender-based differences in bone loss exist.

Further studies are also needed to clarify the relationships among the different systems (musculoskeletal, neurovestibular, nutritional, cardiovascular, etc). A greater effort toward a coordinated, multidimensional approach, with an ultimate goal of prevention and rehabilitation, is required in order to design strategies to counteract the effects or treat as needed, research that will also benefit osteoporosis patients on Earth.

Pharmacological interventions have not been routinely used in space. Programmes designed to rectify the effects of microgravity have focused mainly on exercise. However, it is clear that stimulus from exercise has been inadequate to maintain bone mass because of insufficient load or duration. We know that the number and the amplitude of impacts in orbit are very low compared to those experienced daily on Earth, so any prevention plan should mimic the impacts of daily life on Earth in both number of repetitions and magnitude of force applied.

The “required impact dose” to prevent hip bone mineral density loss has been estimated at 100 impacts per day with a gravitational force of 3.9g, greater than that of Earth at 1g. Future prevention strategies would ideally transiently load the body at more than 1g because of the technical difficulties of loading at 1g throughout the flight. Any programme must be sure to maintain the natural operation of muscle and bone as a single unit working against the force of gravity. Extreme situations, including not only microgravity but conditions such as spinal cord injury or myopathy, can disrupt the normal muscle/bone function. Thus, the frequency and regimen of any prevention strategy have to be carefully studied and defined.

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**Alphabet Soup: DXA, BUA, QCT**

Several techniques exist for measuring bone mineral density. Below is a brief explanation of what each method entails.

<table>
<thead>
<tr>
<th>DXA: Dual energy X-ray absorptiometry</th>
<th>BUA: Broadband ultrasound attenuation</th>
<th>QCT: Quantitative computed tomography</th>
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<tr>
<td>Two X-ray beams with different energy levels are aimed at the patient’s body. One of these beams is absorbed mainly by soft tissue and the other by bone. The soft tissue amount can be subtracted from the total and what remains is a patient’s bone mineral density (BMD).</td>
<td>A bony extremity, usually the heel, is placed between two ultrasound transducers, one transmitting and one receiving. The amount of power lost by various frequencies as they travel through bone and soft tissue—called attenuation—is measured.</td>
<td>Tomography uses digital geometry processing to generate a three-dimensional image of the inside of an object from a series of two-dimensional X-ray images taken around a single axis of rotation. QCT devices are specifically designed for high-precision bone measurements.</td>
</tr>
<tr>
<td>DXA actually measures areal BMD. True density is calculated using mass divided by volume. DXA results can be adjusted by calculating volume based on the projected area.</td>
<td>Attenuation as measured in decibels is used to calculate the BUA index, which varies between normal subjects and those with osteoporosis.</td>
<td>QCT is the only technique that can distinguish between cortical and cancellous bone. It measures volumetric BMD. New bone-dedicated machines are able to evaluate 3-D structure.</td>
</tr>
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</table>

Several techniques exist for measuring bone mineral density. Below is a brief explanation of what each method entails.
Bone Loss in Space

Some reports of increased bone density.

- No bone loss seen at all in forearm after 1- or 6-month missions.
- Bone loss in tibia and heel was greater after 6-month flight than 1-month flight.
- Bone loss in hip greater than loss in spine during 4- to 6-month missions.
- Loss of spongy bone seen in tibia after 1 month in space and continued to decrease with mission duration.
- Bone loss in the spine, femur neck, trochanter (bony crest at the top of the thigh bone) and pelvis after missions up to 7 months.
- Bone loss seen in heel after Skylab 3 and 4. BMD was still below normal 3 months after Skylab 4.

BMD was still below normal 3 months after Skylab 4.
A Brief History of Bones in Space

During the many million of years in which vertebrate animals evolved, the human skeleton gradually stood erect, against the force of earth’s gravity. The major role of the skeleton is to serve mechanical needs of the body to move.

With the start of manned spaceflight in the 1960s, changes in bones became apparent very quickly based on bone radiodensitometry measurements during the Gemini and Apollo flights. Increased urinary calcium and decreased bone mineral density were observed.

In the 1970s, the Skylab missions were more focused on life science objectives, including the study of space-related bone metabolism. Numerous changes were observed: a progressive increase in urinary calcium and then a plateau at 80–100% above normal; calcium balances averaging -200 mg/day on longer Skylab missions; increases in other urinary markers of bone loss of up to 33%. Bone loss in the astronauts’ heels was also found. Months after the flight was over, the density of the heel bone was still significantly lower than normal.

In the 1980s, better research tools and longer missions, such as on the Russian space station Mir, took bone research much further. Computed tomography was used to measure vertebral BMD (bone mineral density) in four cosmonauts after missions lasting up to seven months; all lost vertebral bone density mainly from the posterior vertebra. A dual absorption X-ray photon device showed loss in the spine, femur neck, trochanter (bony crest at the top of the thigh bone) and pelvis of about 1–1.6% per month and 0.3–0.4% per month in the legs and whole body.

Starting in 2000, bone investigations were conducted in crew members of the ISS missions using computed tomography measurements of the hip and spine in addition to the routine dual X-ray absorptiometry measurements. Pre- and post-flight measurements were done in 14 subjects who performed 4- to 6-month missions. ISS crew members experienced substantial loss of both trabecular (inner layer) and cortical (outer layer) bone in the hip and somewhat smaller losses in the spine. Taken together, it seems that there is a gradient of mineral loss beginning at the lumbar spine level and becoming progressively greater in the lower limbs.

Research results indicate that recovery of skeletal density after long-duration space missions may exceed twice the time spent in microgravity conditions. Prevention strategies so far have focused on exercise, but they have been inadequate. Future study must focus on the dynamics of skeletal changes as well as the right type of exercise or preventive movement to combat the loss of gravity.
Our Sensitive Skeleton

You’re playing a game of word association. Your partner says mother; you say father. Your partner says cat; you say dog. Your partner says skeleton; you say … what? Perhaps you respond with strong, or even Halloween, but you probably do not say sensitive. Although we rarely if ever associate it as such, bone tissue is sensitive to its mechanical environment, a condition known as mechanosensitivity, which allows bone tissue to adapt during the course of a lifetime for more efficient performance. This adaptation is a cellular process by which bones alter their mass and structure in response to the demands placed on them; and to adapt, bone tissue needs a system that senses the mechanical load or stress on bones. Then, this loading information must be communicated to the “effector” cells that have an active role in bone remodelling, or turnover. Bone cells continuously dissolve and then rebuild bone tissue. This occurs throughout adult life, where bone tissue is resorbed by osteoclasts and new bone matrix deposited by osteoblasts.

The ability of bones to adapt is part of the reason why larger animals like elephants have corresponding wider bones than say, humans. Galileo Galilei was probably the first to describe the role of gravity, i.e., weight, on living organisms. He observed the dimensions of bones from animals of different weights and noted that the length-to-width ratio was remarkably different between light and heavy animals. The very act of carrying body mass around places a heavy mechanical load on bones. The reverse is also true. If the mechanical load is lower than normal due to situations such as bedrest or immobilization, bone mass decreases in a condition known as disuse osteoporosis.

Since the earliest space flights, the negative effect of prolonged weightlessness on astronauts’ bones has been of critical concern. Spaceflight produces a unique condition of skeletal “unloading” as a result of the near-weightless conditions. Bones are no longer subject to the gravitational pressure normally experienced on Earth, and, like bedrest, this results in bone loss.

Experiments performed during spaceflight have shown that microgravity acts directly on skeletal tissue without the influence of systemic factors such as stress hormones (see Figure 1). The exact mechanism of how bone loss occurs in spaceflight is still unknown and many questions remain. How is the lack of gravity detected? Can near-weightless conditions act directly on bone cells? Could certain cells read the gravitational field change directly? To answer these questions, the fundamental properties of the way bone cells respond to loading in general have to be addressed.

Bearing the Load

Although adaptation is a general phenomenon and not specific for bone tissue, it is intriguing that such a hard and seemingly inert material as bone can be gradually altered during life, and in such a “sensible” or sensitive manner. All eukaryotic cells (cells having a nucleus) are probably sensitive in some way and physical factors, including gravity, tension, compression and shear, influence growth and remodelling in all living tissues. In vertebrates, bone is the tissue best suited to cope with large forces because of its hard but flexible extracellular matrix, a tough composite material outside the cell walls that provides structural support to the cells in addition to other important func-

AT A GLANCE

- Bone cells can sense the load or stress placed on them and can adapt according to these mechanical demands.
- Studies suggest that the rate of the strain or movement is more important to building bone than the amplitude or power required to execute it.
- These findings have direct implications for the type of exercise or other preventive strategies that may work to counteract the extreme “unloading” that occurs in space.

—The Editors
Galileo was the first to notice the effect of weight—or gravity—on bone size. But if bone tissue can sense and react to gravity, how are those processes affected once gravity is removed?

By Rommel G. Bacabac, Jack J.W.A. van Loon and Jenneke Klein-Nulend

Mechanical adaptation ensures efficient load bearing: the daily loads are carried by a surprisingly thin structure.

The organisation of the cellular activity behind this adaptation is poorly understood, but over the last few years significant progress has been made. These studies emphasize the role of the osteocytes, the most abundant cells in adult bones, as the professional “sensor” cells of bone.

These load-sensing osteocytes are in contact with each other via their long slender cell “fingers” that reach through tiny canals within bone called canaliculi. The osteocytes themselves lie in a space called a lacuna, Latin for “pit” (see Figures 2 and 3). The space between the cell body, its “fingers” and the bone matrix is filled with fluid. This network of interconnected cells surrounded by fluid can efficiently detect local changes in stress. When a heavy load is placed on bone, the result is something like squeezing a wet sponge. The bone becomes deformed and causes fluid to flow through the canaliculi, which activates the osteocytes (see Figure 4) and transports cell signalling molecules, nutrients and waste products. One of these signalling molecules is nitric oxide (NO). The quick-responding osteocytes react to the fluid flow by activating the enzyme responsible for NO production.

**FIGURE 1. GROWTH OF EMBRYONIC MOUSE LONG BONES IN SPACE.** Bones from 16-day-old mice were cultivated under different gravitational conditions. (A) Growth immediately after isolation; (B) Cultured under Earth’s gravity of 1g on the centrifuge during flight; (C) Cultured under microgravity conditions in the Biorack facility. During the 4-day culture period, calcification starts in the centre of the embryonic bone, which is clearly visible as a black spot in the centre (D). The calcified section of the bone cultured in microgravity was significantly smaller than when cultured under Earth’s gravity on the centrifuge. TL = total length of bone.
Mechanotransduction in Bone

Exactly how a mechanical signal is detected and converted into a chemical, intracellular response—processes called mechanosensing and mechanotransduction, respectively (see Figure 4)—has yet to be established. The composition of the bone matrix immediately surrounding the osteocytes and their attachment to that bone matrix appears to be very important. The bone matrix determines how porous the bone is, and thus the rate and pressure of the fluid flow in response to stress. As stated above, the “fingers” of the osteocytes reach through bone to detect and also amplify deformations that occur with pressure. In addition, osteocytes are capable of producing proteins and “filler” substances that exist between cells; so they might also be able to adapt the porosity of the matrix around them as part of the loading response.

Osteocyte receptors attached to the extracellular bone matrix are prime candidates for mechanosensing. In addition, each osteocyte (as well as all other cells) has its own dynamic skeletal structure aptly named the cytoskeleton that not only provides scaffolding for the cell, but also contains “trans-membrane” proteins, which do as their name implies. They cross the cell membrane to link the internal structure of the cell to the bone matrix outside, and any sensation of force is likely registered through the communication of these connector proteins. The rapid release of NO by bone cells under stress makes NO an interesting candidate for communication within the network of bone cells. In addition, the production of the bone matrix protein osteopontin by osteocytes rapidly increases the amount and timing of changes to bones after acute disuse, which may mediate bone resorption.

Bone cells are not the only cells to exhibit this kind of stress response, and not the only cells to use NO as a signal. In the vascular system, changes in the diameter of arteries occur in response to changes in rate of blood flow in order to ensure a constant vessel tone. (See “Counteracting Hypertension with Weightlessness?” on page 16.) Endothelial cells, which line not only blood vessels but also other internal cavities, are widely recognized as the sensory cells in this case. Like the osteocytes, endothelial cells respond to fluid flow with the release of NO and signalling molecules. While it is surprising that such different systems seem to use a similar sensory mechanism, this concept explains local gains and losses in bone as well as the remodelling that occurs after damage.

Quality, not Quantity

Several studies suggest that the rate of the mechanical strain is more important to bone formation than the magnitude of the strain. Low-magnitude (<10 microstrain), high-frequency (10–100 Hz) loading has been shown to stimulate bone growth and inhibit disuse osteoporosis. These data make sense from an evolutionary standpoint. Low-amplitude, high-frequency stimuli such as that experienced when walking are fairly common in daily life, where-
as occasions for high-amplitude, static strain such as lifting heavy objects are more rare. In studies of rats with osteoporosis, bone mass and strength both increased after jumping exercises, indicating a frequency-related response in bone formation.

In another study, in vivo measurements were taken of the human hip bone while walking and jogging, and the results showed that the strains experienced during these activities have a rich frequency spectrum. This implies that despite the minute level of strain, the speed of the impacts when walking or jogging could account for the quality of the exercise. Studies of bone cells showed that the increase in NO correlated linearly to the rate of fluid shear stress in the canaliculi. That is, bone cells respond better with faster stimuli. This supports the notion that bone formation is stimulated by dynamic rather than static stresses, and that low-magnitude, high-frequency exercise may be as stimulating as high-amplitude, low-frequency exercises. In studies of bone cell responses to vibration stress using a wide frequency range of 5–100 Hz, the release of NO correlated with the maximum acceleration rate. This correlation may be related to oscillations of the nucleus, which is more dense than the cytoplasm and more apt to be “felt,” providing a physical basis for how cells sense high-frequency loading.

The corresponding reaction of bone cells to fluid shear stress provides a physical rather than evolutionary explanation as to why adaptive bone formation occurs despite the sporadic occurrence of high-amplitude strains in daily life. Further understanding of how bone cells respond to stress might provide a deeper insight on how living bone is able to sustain itself with the occurrence of meagre strains, whereas cultured bone cells are known to require greater strain. One explanation may be that sporadic release of a signalling molecule is adequate for sustained bone health.

You Can Feel It in Your Bones
Although stiff, bone can feel very small levels of strain, possibly even from flexing the muscles. It makes sense to have healthy muscles along with healthy bones. One study has shown that whole body bone mineral content as an indicator of bone strength correlated to lean body mass as an indicator of muscle strength. This implies that muscle activity can influence healthy bone growth and that bone tissue can be highly sensitive to minute strains. As stated earlier, bone prefers the quality of stress rather than its quantity.

Vibrating plates and ultrasound have also been used to create low-magnitude, high-frequency stress, and both methods seem to effectively stimulate bone cells; however, how the forces are transferred to the effector cells through soft tissue barriers of skin, muscle and so on is not straightforward. In fact, the stimulation of bone cells may not directly result from the transfer of force to the cells themselves. If the intervening soft tissue serves to further weaken an already meagre source of stress, there may be other processes or cellular com-
When a heavy load is placed on bone, the bone tissue squeezes like a sponge and fluid flows through pores called canaliculi. This fluid flow is essential for osteocytes to "sense" the load or stress and respond appropriately.

When the proper amount of noise is present, bone cells can respond appropriately to a "noisy" stimulus, such as that caused by muscular vibration, ultrasound or vibratory motion, and characterized by low-magnitude high-frequency strain.

Response to Cell Deformation
The response of the bone cells is not only correlated with the magnitude and frequency of the mechanical load, it also depends on the deformation of the bone cell under stress, the cytoskeleton and trans-membrane proteins linking the cell to its surroundings and even other cells. Now, studies have shown that, when bone is "squeezed" like a sponge under heavy loads, those cells deformed by exposure to fluid flow release more of certain signalling molecules compared with cells deformed by the stretching of bony surfaces to which they are attached. Cellular deformation caused by fluid flow has a greater effect on the bone cells, while the effect of surface strain is focused on the cell-surface attachments.

We have observed the process of cell deformation in a simple laboratory model. In the body, osteocytes are attached to the extracellular matrix, and they sense a load or force once that matrix starts to deform under the stress of the load. At this point, the osteocytes adapt by pulling on the attachment sites. In the lab, we attached a single cell floating in medium to small spheres of 2.5 microns on its opposite ends. By wiggling one of the spheres or beads, the cell is made to experience minute forces of less than a tenth of the cell's weight. However, the traction force induced by the osteocytes themselves is relatively high—more than twice their own weight—and they release NO simultaneously with increasing force application. We also observed that the cells adapt to the traction force by changing their morphology from a spherical to an elongated shape. These experiments demonstrate a strong link between the processes involved in force sensing and force induction as well as the release of signalling molecules by cells.

Use It or Lose It
Findings that the rate of mechanical loading is more important than magnitude for bone health have powerful implications on the local activity of osteocytes in directing adaptation. Under extreme conditions of unloading such as near-weightlessness, it might be possible to counteract the onslaught of bone loss with sporadic...
bouts of rapid-impact exercise, since the “quality” of exercise as recognized by bone would depend on the speed of the strain, despite the minute amount. Currently, bone loss prevention is based on either exercise or pharmaceutical applications, but the approach must eventually target the bone cells. As discussed, bone loss results from a disturbance in stress levels, the amount ofsignalling molecules released, and their roles for directing local bone remodelling. Since these parameters are closely related, it might be possible to restore their stability despite extreme conditions of unloading.

Scientists have considered whether bone cells are able to read the changes in the gravitational force directly or detect these changes indirectly via contact stresses. It seems that the light weight of cells undermines the role of gravity in their behaviour. At the molecular level, gravity has only a small role because movements are determined by diffusion (Brownian motion) or by specific molecules that induce much higher forces compared with the weight of the molecules themselves. Thus, the question remains as to how osteocytes might detect near weightlessness directly.

Studies have also shown that the organisation of the cytoskeleton is gravity dependent and that this organisation may affect particle transport within the cell. Any reorganisation of cellular components has implications on properties like elasticity and viscosity, which would affect how the cells sense forces. If gravity affects the relation between cytoskeletal organisation and intracellular transport, then the gain or loss of these forces—and corresponding impact on structure and transport—may enable cells to directly detect gravitational changes. Thus, it is possible that the signal for gravity fluctuations comes from inside the osteocytes and these cellular changes influence bone cell sensitivity.

Apart from the obvious disuse effects of microgravity, the effect of spaceflight on fluid distribution in the human body may be another consideration. Without gravity to pull blood and other fluids to the lower part of the body, these fluids move more freely to the torso and head. There are data suggesting that, in humans, bone mineral loss during spaceflight is unevenly distributed throughout the body, being most pronounced in the legs and pelvis. In the head only a small but significant increase in bone mineral density has been observed. Thus, changes in bone mineral density seem to correlate with changes in interstitial fluid pressure. In this model, reduced fluid pressure leads to reduced fluid flow through the canaliculi, whereas increased fluid pressure would increase fluid flow. This is compatible with bone loss in the former situation and bone gain in the latter, which provides indirect evidence for a relationship between fluid pressure and bone balance. Currently no direct studies are underway to link these two properties, but it may be worthwhile to analyze a possible relationship, and manned spaceflight studies could offer unique conditions to test this hypothesis.

**Conclusion**

Tremendous progress has been made toward understanding the function of osteocytes since the first experiments on bone loss in astronauts were performed. Information has increased regarding their potential functions and response to strain. Molecular mechanisms and pathways involved in osteocyte mechanosensation have been identified and expanded significantly. It remains to be determined whether the loss of gravity affects the way these cells sense forces, leading to bone loss during spaceflight. The future of scientific study in this area looks exciting with great potential for discoveries surrounding the osteocytes’ role in sensing stress and their function under microgravity. New insights will help to develop treatment strategies to prevent dangerous bone loss in astronauts.

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**Ebb and Flow**

On April 19, 2004, the Dutch Soyuz Mission “DELTA” (Dutch Expedition for Life Science, Technology and Atmospheric Research) was launched on its way to the International Space Station. On it was the authors’ entry into biological experiments in microgravity. Called the “Flow” experiment, it was designed to test whether the osteocytes’ production of NO and other signalling molecules changes when in microgravity versus when on Earth. Cultures in flight were subjected to both microgravity and simulated Earth gravity using a centrifuge inside the Kubik incubator. Control cultures on the ground were subjected to identical culture environment and stress stimulations. Unfortunately, hardware malfunction resulted in a lack of electronic power to flight containers. Despite this setback, the preparations for the experiment indicate that this setup is viable for a future flight opportunity. The experiment has been considered as a potential candidate by the European Space Agency for one of the next Soyuz missions.

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High-precision experiments performed in space will put some of Einstein’s theories to the test.

By Stefano Vitale, Christophe Salomon and Wolfgang Ertmer

Gravity is everywhere. It is the reason an apple falls to the ground and why galaxies gather in clusters stretching across millions of light-years. It pervades the universe, despite being the weakest of the four fundamental forces. Thanks to Einstein and his theory of general relativity, our understanding of gravity has progressed enormously. Since the publication of his theory in 1916, a number of experiments and observations have confirmed many of its basic tenets.

AT A GLANCE

- Gravity is a universal force that acts consistently on all bodies; Galileo proved two bodies fall to Earth at the same rate. All experiments in physics yield in free fall the same results as in the absence of gravity.
- Atomic clocks use atomic resonances to measure time and can accurately test Einstein’s predictions. Gravity limits their accuracy because atoms “fall” past the sensor. On the ISS, the atoms “float” longer near the sensor for more precise measurement.
- Einstein said that when matter accelerates it emits gravitational waves. Satellites in development will allow the detection of these ripples as they pass by, a gravitational snapshot of the universe.
- What happens if future testing shows that Einstein’s theories are slightly off? Many theorists are hoping for that to get a hint on how to reconcile gravity and the quantum world, an unsolved fundamental question in our understanding of the universe.

—The Editors
However in some key situations, gravity remains poorly understood, such as within the violent environment of a black hole. Here, conditions are so extreme that nothing escapes the black hole’s grasp except gravitational waves! In addition, how gravity operates within the limits of quantum mechanics, something that must have occurred during the very early stages of the universe, is still a mystery.

One of the most difficult tasks for physicists today is measuring gravity with sufficient precision to understand how it works at these extreme boundaries of our knowledge. An upcoming experiment onboard the International Space Station and others on a series of sophisticated space probes may provide some answers.

**Timely Measurements**

In the late 16th century Galileo Galilei recognized that in a vacuum, objects of different weights, such as a cannonball and a feather, fall toward the centre of the Earth accelerating at exactly the same rate of 9.81 m/sec². So, in practical terms, if you fall off a cliff during a mountain hike one thing you wouldn’t have to worry about is losing your rucksack or camera because they will fall with you at exactly your rate of descent (ignoring any effects of air resistance). They will appear to “float” around you as you plunge toward the ground, almost as if gravity doesn’t exist.

Known as the principle of equivalence, this condition is a fact of life on the ISS. Astronauts,
nuts, bolts and bits of equipment all appear to float as if gravity has been switched off. In reality, everything is in free fall, even the space station itself. As it falls, however, it moves forward fast enough that it never actually plummets Earthward. It keeps falling past Earth as it orbits the planet.

For many experiments the ability to eliminate gravity is a major advantage, and for many researchers, the ISS provides an excellent laboratory to study natural phenomena without the impediment of gravity. Take clocks, for instance: they are a key instrument in the study of gravity.

**Atomic Flip-out**

Atomic clocks are the most precise clocks that exist. They use resonance frequencies of atoms in certain elements, usually caesium or rubidium, to keep extremely accurate time. Today our definition of a unit of time is based on exposing a free-flying, undisturbed atom of caesium-133 to microwaves. Quantum mechanics tells us that when the energy of the microwave signal is equal to the energy separating two quantum states of the caesium atom, the atom flips from one state to the other. One second of time is defined as 9,192,631,770 times the period of oscillation of the microwave signal that makes a caesium atom flip between two of its quantum states.

However, this applies only to undisturbed atoms, which is a fundamental limitation. The problem is that when an atom is released on Earth, gravity takes over. The atom acquires a speed of one metre per second in just one-tenth of a second, and it accelerates downward with every passing moment. So the best a physicist can do is to make a brief observation as the atom zips past a detector. To obtain more accurate measurements, the atom needs to be observed for the longest possible time.

In the microgravity environment of space, an atom can be kept in an observable volume for up to tens of seconds. On the ISS, atoms can be slowly launched in free flight across a two-microwave-field zone tuned to the “magic” quantum-flip frequency—the frequency of the quantum jump between the energy levels of the atoms being used for the clock—and observed for many seconds.

This is the feature that will be exploited by the Atomic Clock Ensemble in Space (ACES), to be located on the external platform of the Columbus module on the ISS in 2012. Laser beams will cool caesium atoms; the slow atoms and their low acceleration in microgravity will allow observation times significantly longer than is possible on Earth.

ACES is expected to reach an accuracy of 1 part in $10^{16}$ (one followed by 16 zeros). In terms of time, this is equivalent to a clock being off by one second every 200,000 million years!

**The Relativity of Time**

One of the predictions of general relativity is that gravity affects clocks and the measurement of time. Actually it is not just gravity. Relativity also dictates that the speed of light—the distance light travels per unit of time—is the same for all observers: 299,792,458 m/sec. It may not be obvious, but this also affects the measurement of time.

Suppose a beam of light travels from the final car to the engine of a rapidly moving train just as it passes through a station. To an observer on the train, the light will travel precisely the length of the train in X amount of time. But to an observer standing on the platform while the train passes by, that same light beam will travel the length of the train plus the distance travelled by the train during the experiment. As the velocity of light is the same for both observers, the clock of the person on the platform must measure a time longer than X. The time between events, the emission and collection of the light beam, is different for observers who see each other moving at velocities greater than zero.

Just as velocity affects clocks, so does gravity. Compare for instance a clock on the top of a tower with an identical one placed at its bottom. Each time the bottom clock ticks, it also sends out a flash of light, so that while sitting at the tower top, you can compare the ticks of the bottom clock, as marked by the flashes, with those of the clock at the top. To avoid being confused by the effects of gravity, imagine the observer is free falling, which cancels out the effects of gravity. While the observer accelerates downward, he sees the tower and the clocks accelerating upward. With the tower top moving further away with constantly increasing speed, the flashing light that is travelling at constant velocity will have to cover a constantly increasing distance. The flashes will thus be received at longer time intervals than those with which they have been emitted. The bottom clock appears to run slower than the top one.

This may seem like a theoretical exercise, but it is something that cannot be ignored even in daily life. If you navigate using a global posi-
tioning system (GPS), and the software doesn’t correct for gravity and the satellite’s velocities, your GPS will locate you many kilometres from your actual position.

The ticking of clocks in different gravitational fields is so rooted in our understanding of the principle of equivalence and the general theory of relativity that it has been tested repeatedly with ever-increasing precision. The most accurate measurements to date have been obtained by NASA’s Gravity Probe A. A hydrogen maser (microwave laser) atomic clock was launched on a two-hour suborbital rocket flight to an altitude of 10,000 kilometres. The time of the onboard clock was compared with two identical maser clocks on the ground. Einstein’s theory was confirmed to an accuracy of 70 parts per million.

ACES, with its more precise clock, is designed to improve Gravity Probe A’s test of the theory of relativity by as much as a factor of 30, thereby providing a new challenge to Einstein’s theories.

**Relative Gravity**

Running experiments in microgravity can be useful. Free fall “turns off” gravity and actually improves the operation of some instruments. But for scientists studying gravity itself, this cancellation is not a good thing. To make matters worse, it turns out that free fall is unavoidable. This not a paradox. For example, we all fall together, with the Earth, around the sun. Thus on Earth, the gravity of the sun (and any other celestial body) is turned off and so cannot be measured.

However, the cancellation of gravity in free fall is not perfect. For instance the sun’s gravity pulls everything toward its centre. Thus falling particles will converge toward that point and their paths will not be parallel. Also, objects close to the sun feel a more intense gravitational pull than do objects farther away, which causes greater acceleration for the closer objects. The result is a compromise: most of the sun’s gravity is cancelled by free fall, but small, localized differences remain. On our planet, these slight differences squeeze and pull Earth’s oceans, resulting in the small relative accelerations that we know as tides—the only measurable effect of the sun’s gravity on Earth.

If a beam of light travels through a fast-moving train as it speeds through a station, the time for the light to travel from one end of the train to the other will be different for an observer on the train versus one standing on the platform. To the person on the train, the light travels the length of the train only in X time. But to the person on the platform, that same light travels the length of the train plus the distance travelled by the train.

**On our planet, these slight differences squeeze and pull Earth’s oceans, resulting in the small relative accelerations that we know as tides—the only measurable effect of the sun’s gravity on Earth.**
Imagine two of these free-falling particles and plot their separation as a function of time. The result is a graph of space–time: one axis is a space coordinate, the other is time. If the particles are moving at a constant velocity, then the distance the particles travel is proportional to the time elapsed, and the plot is just a straight line. In ordinary, flat space, a straight line is the shortest path between two points and is called a geodesic. In four-dimensional space–time (where there are three directional coordinates plus time), things are a bit more complicated, but still, in the absence of gravity, a straight line is a geodesic. So in the absence of gravity, particles follow geodesics in space–time. However, if gravity accelerates one particle relative to the other, the rate of their separation change varies with time, and the plot bends away from a straight line.

In the theory of relativity, Einstein showed that particles even in this case still follow geodesics. Because gravity curves space–time, however, geodesics are no longer straight lines. This is similar to what happens when a particle is moving on the curved surface of a sphere. The shortest path between two points is not a straight line but an arc of a circle with same radius as the sphere.

Ripples in Space–Time
While Einstein’s theory of relativity is our best model for explaining gravity, some of its predictions are mind-boggling. For instance it predicts that when matter accelerates, it causes ripples of curvature in space–time. These space–time ripples move at the speed of light and are known as gravitational waves.

Intense gravitational waves were likely generated during the Big Bang, but there are other candidate sources, for example, two black holes orbiting each other. Such pairs are expected to be quite common as there is strong evidence that almost every galaxy carries, at its centre, a gigantic black hole up to billions of times the mass of the sun. And galaxies often collide as they

Some evidence strongly suggests that every galaxy has a black hole at its centre that is up to billions of times the mass of the sun. Because galaxies often collide, their core black holes could form a binary system. If two black holes do merge, a powerful burst of gravitational waves would occur.
wander through the universe, which gives their core black holes the opportunity to form a binary system. If two black holes eventually merge, the result will be a powerful burst of gravitational waves.

Gravity waves are not just theoretical constructs. In 1974 a binary pulsar was discovered, in which the two stars are slowly spiralling inward toward each other. This will happen if the system loses energy by emitting gravitational waves. It turns out that the stellar pair’s inward spiral is occurring at exactly the rate predicted by general relativity. So astronomers have detected a signature result of gravitational waves but not the waves themselves. That may soon change.

In the upcoming ESA–NASA mission called LISA (Laser Interferometer Space Antenna), three pairs of gold–platinum particles will be set at the apexes of a triangle five million kilometres on a side. These pairs of free-falling particles, when hit by a gravitational wave, will feel a tiny oscillating acceleration (relative to each other). A very precise motion sensor (a laser interferometer) will be able to detect an oscillation of the relative acceleration of these particles in the range of one billionth of a billionth of the acceleration caused by the Earth’s gravity.

When LISA is operational (perhaps as early as 2019), it will open a new observational window on the universe. Astronomers hope to detect gravitational waves generated by the earliest moments of the birth of the universe. Signals from the supermassive black-hole binaries scattered across the universe will help scientists probe the large-scale structure of the cosmos. The death of small objects spiralling into a black hole will generate gravitational waves that should provide a map of the gravitational field surrounding the hole. In short, astronomers will finally get a close look at how gravity behaves in extreme conditions.

All Things Considered Equal

The principle of equivalence is such a central pillar of our understanding of how the universe behaves that it is legitimate to ask the limits of its validity. On Earth it has been demonstrated...
that this principle is obeyed to at least the 13th decimal point. In other words, the measured accelerations from all the physical systems that have been studied fall within this very small margin of error. However, this is about the limit that can be reached in a standard laboratory on Earth because of the constraints of gravity.

So the French Space Agency, in collaboration with ESA, is developing a satellite called Microscope to test how well the principle of equivalence is obeyed in space—with an accuracy 100 times greater than what can be accomplished on Earth. Two pairs of solid test-masses made from different materials will free fall in Earth’s orbit, and their acceleration will be measured with an accuracy of one part in one thousand billion.

Can the study be pushed even further? How well might the principle of equivalence hold up for small quantum particles and not just for ordinary, solid matter? Can a test comparing the rate of fall of just a few isolated atoms be performed?

**Chilled Out**

According to quantum mechanics, matter can behave like particles or waves. As a wave, light can pass through a grating or slit in an optical device and create interference patterns. Similarly, an atom behaving as a wave can create interference patterns. In an atom interferometer the gratings and the slits are created by cleverly combined laser beams that guide the atoms along a determined path.

For an atom-wave, its wavelength is directly related to its velocity. Any acceleration of the atom will alter its wavelength and cause changes in the interference patterns, making an interferometer ideal to detect tiny acceleration differences between free-falling atoms. So in theory a quantum-level test of the principle of equivalence is possible, but can it be carried out?

Interferometers for atoms are not easy instruments to work with. Because the atom’s wavelength is inversely proportional to its velocity, and because the larger the wavelength the more precise the measurements can be, the slower the atom moves through the interferometer, the better. The challenge is to create an environment conducive to very slow-moving atoms, and that turns out to be a cold environment.

This is achieved with laser cooling, a technique that uses laser light as a braking mechanism to slow the velocity of the atoms to as low as a few millimetres per second. (In comparison, the random velocities of atoms in a gas at room temperature and standard pressure can be a few hundred metres per second). In microgravity, this speed limit can be pushed even lower, perhaps to less than 0.001 mm/sec. This is the speed at which atoms move when the temperature is less than one hundred billionth of a degree above absolute zero (approximately -273°C).

Various research groups are actively developing space-borne, cold-atom interferometers. ESA supports some of these studies through its ELIPS research program. Prototypes have already been tested in free fall, albeit for the short duration achievable on a drop tower in Bremen, Germany (a facility where an experimental capsule is dropped from a great height in order to achieve a few seconds of free-fall). When these experiments finally arrive at the ISS or some other space-borne platform, the principle of equivalence will meet a new challenge.

**What a Drag**

One complication is that the ISS does not actually provide a perfect, gravity-free environment. Mundane disturbances, like the residual drag of Earth’s upper atmosphere on the ISS, will accelerate the station out of its trajectory. A perfect zero-gravity situation can be achieved only if no other force acts on the laboratory itself. Admittedly, it is not necessary for these external forces to be exactly zero. If they can be measured, it might be possible to compensate for them.

This is the idea behind the so-called “drag-free” technique that forms the basis of the ideal gravitational lab. It consists of a small but heavy test mass floating freely inside a spacecraft. A gravitationally quiet environment is created in the neighbourhood of this test mass so that it falls as freely as possible under the influence of gravity alone. A position sensor—a laser interferometer or a proximity sensor—measures the position of the test mass relative to the spacecraft without making physical contact. If non-gravitational forces such as air drag or solar-radiation pressure act on the spacecraft, the test mass will appear to accelerate. To compensate, the spacecraft’s engines are activated to adjust its flight path to follow the test mass. As a result the spacecraft tracks the pure free-fall trajectory of the test mass and counteracts any external disturbances.

Trying to gently adjust something as massive as the ISS is pretty much an impossible task. Thus, any experiment, such as one testing the principle of equivalence or searching for gravitational waves, that needs a perfect free-fall envi-
LOOKING UP: Europe’s Quiet Revolution in Microgravity Research

The environment will require a special drag-free satellite. In the case of Microscope, the spacecraft will use tiny ionic microthrusters, which adjust the craft via the recoil from a jet of metal ions forced from an onboard liquid reservoir. The force required to compensate for the atmospheric drag present in low Earth orbit is miniscule—on the order of 10 millinewtons. This is less than the force needed to lift an ordinary sheet of paper.

LISA’s requirements are even more demanding; an environment for its free-falling particles that is almost one thousand times more stringent than for Microscope. A disturbance equal to the force necessary to lift a small bacterium will disrupt LISA’s measurements! Although LISA’s interplanetary environment will be much quieter than Microscope’s (because LISA will be situated farther from Earth), it is valid to ask if LISA’s particle pairs can really be set in motion along pure space-time geodesic tracks with such minimal relative acceleration from outside forces. Such a question can only be answered by a test, and unfortunately the experiment can be performed only in the microgravity of space. This difficult task belongs to LISA Pathfinder.

Challenging Einstein

What happens if the results of any of these tests disagree with principles of the theory of relativity or, at a more fundamental level, with the principle of equivalence? If that is the case, physicists will have to consider other theories or new fundamental interactions.

Theorists are not waiting for experimental results. Instead, they are continuing to try to model the behaviour of gravity in extreme conditions where quantum physics comes into play. Some of these models predict extremely weak interactions between particles. If this is the case, precise measurements, such as those about to be attempted, may reveal tiny deviations from the principle of equivalence and the other basic principles of general relativity. Such deviations would give physicists their first real indication of gravity’s behaviour at the quantum level, which dominated the early stages of the Big Bang and a concept that Einstein was unable to come to terms with. The general theory of relativity has stood the test of time remarkably well. But perhaps now we can finally begin to probe its limits.

Probing Gravity

Three European projects designed to probe gravity are already underway.

**LISA Pathfinder** will pave the way for a major ESA/NASA mission planned for the near future: LISA (Laser Interferometer Space Antenna), whose goal is detecting gravitational waves generated by massive objects such as black holes.

It consists of two test-masses in a nearly perfect gravitational free-fall, and of controlling and measuring their motion with unprecedented accuracy. Such technologies are essential not only for LISA; they also lie at the heart of any future space-based test of Einstein’s theory of general relativity.

**ACES** (Atomic Clock Ensemble in Space) will bring a new generation of atomic clocks in the microgravity environment of the ISS. The ACES payload will distribute a stable and accurate time base that will be used for space-to-ground as well as ground-to-ground clock comparisons. The direct comparison of ultra-precise atomic clocks is crucial for the exploitation of ACES potential in many different areas of research.

**MICROSCOPE** (MICRO Satellite à traînée Compensée pour l’Observation du Principe d’Équivalence) is a part of the microsatellite line of CNES (Centre National d’Études Spatiales, France). The objective of the project is to test the principle of equivalence with an accuracy of $10^{-15}$. 

CGS has been Prime Contractor of ESA for the development of the LISA Inertial Sensor Engineering Model and is Prime Contractor of ASI for the team developing the LTP ISS (Inertial Sensor Subsystem).
Moving in Flow-Motion
A malfunctioning fuel pump and a harrowing near-disaster at Heathrow Airport illustrates the necessity of understanding fluid flow dynamics. Removing gravity from this complex equation allows for new and exciting research in this area.

May the capillary force be with you!

By Michael Dreyer, Ilia Roisman, Cameron Tropea and Bernhard Weingartner

Just after midday on the 17th January, 2008, a British Airways Boeing 777 made its final approach to London’s Heathrow Airport. At 220 metres in elevation and 3.2 kilometres from touchdown, the autothrottle demanded increased thrust from both engines. Nothing happened. The pilots took over but could do nothing. After skimming across the roofs of nearby houses, the aircraft thumped into the grass border some 300 metres short of the runway. The 152 passengers and crew left the plane via the emergency exits, terrified and bewildered by what had happened.

And what did happen? In May, the Air Accidents Investigation Branch concluded, “...that both engines had low fuel pressure at the inlet to the HP [high-pressure] pump. Restrictions in the fuel system between the aircraft fuel tanks and each of the engine HP pumps, resulting in reduced fuel flows...work has commenced on developing a more complete understanding of the dynamics of the fuel as it flows from the fuel tank to the engine.”

Understanding how fluids work really does matter. It touches our lives in ways that we do not realise: from the beauty of gravity-defying water droplets clinging to buds and twigs on a damp spring morning to fluid flow choking in a high-pressure pump inside an aircraft engine. Although we have learned a great deal about fluid flows during many years of patient research, much of the science still remains mysterious. Venturing into space to disentangle gravity from the equation opens up exciting new avenues of research and provides greater insights into this fascinating subject.
**The Basics of a Strange Brew**

Fluids are strange. A liquid fills a glass above its rim but does not overflow. An insect scuttles across the surface of a pond as if walking on solid concrete. How is this possible?

Every molecule in a liquid is pulled equally in all directions, resulting in a net force of zero. At the liquid’s surface, however, a molecule is attracted more by the interior fluid than by the outside environment. But the force that pulls the molecule toward the liquid’s interior is balanced by the resistance of the fluid to compression, which causes the surface of a liquid to behave like a stretched elastic membrane. This effect is called surface tension (attraction), which in turn gives rise to capillary forces (adhesion). These forces can be stronger than gravity; this is interfacial fluid flow in action. The importance of these forces increases dramatically in flows over short scales (length or distance covered), but at smaller and smaller scales the investigation of such flows becomes increasingly difficult to control or measure.

This situation changes in microgravity, and even in flows over long scales, the influence of capillary forces can remain significant. This is why microgravity represents a powerful tool for scientific research in this field. And what better place to start than with spacecrafts themselves, since in the absence of gravity they are afflicted by numerous fluid flow problems.

**To Boldly Flow**

All spacecrafts, whether simple meteorologic satellites or complex space stations, are dependent on and limited by fluid flow physics and engineering technology. Spacecraft components such as propellant tanks, heat-transfer units and life-support systems contain liquids, and these liquids must be moved around. In microgravity the effects of natural convection, sedimentation, buoyancy and hydrostatic pressure are significantly altered and cannot be used to position, pump, separate, stratify or destratify fluids—with or without free surfaces.

Fortunately, in the absence of gravity capillary forces can be much more dominant than on Earth. These forces can be used to pump and position liquids without the necessity of moving parts or hydrostatic pressure. For example, capillary channels (liquid-acquisition devices) are widely used in propellant-management systems to position and pump liquid toward external thrusters.

The advantage of this technique is that the inlet may be anywhere along the axis of the flow channel. As long as the bulk of the liquid is connected to the channel, liquid can be withdrawn. Additional devices, such as refillable reservoirs, ensure that bubble-free liquid is provided to the spacecraft’s thrusters. An important prerequisite to designing and using such devices is a fundamental understanding of how to model structures that contain liquids with partially free surfaces for propellant management in space.

A simple containment structure is called a parallel-plate capillary channel (see Figure 1). Two liquid menisci (the curved surface of a standing liquid) are formed between parallel plates. External forces, such as a pressure drop created by a pump, drive the flow of liquid through the channel. Due to pressure gradients...
along the channel’s axis, the curvature of the free surface changes in the direction of the flow. At a certain flow rate, surface pressure can no longer be balanced by internal pressure, and the surfaces collapse. For reasons not yet fully understood, this stability limit depends on the geometry of the channel and the properties of the liquid. So a key goal of ongoing research is to find and explain these limits.

**Choking on Fluid Flows**

To understand the interaction of flow with a free surface, several parallel-plate experiments were conducted in the low-gravity environment of a drop tower and non-orbiting, short-duration sounding rockets. A silicon fluid was used with a flow rate that varied between 4 and 8.4 ml/sec. Videos were shot during the flight of the Texas-37 sounding rocket, which provided six minutes of microgravity time.

When flow rates are below a critical value, the free surface remains stable and its curvature increases with increasing flow rate. If the steady-flow velocity at the throat of the flow path is increased above a critical value, ingestion of gas occurs and the flow rate of the liquid is restrict-
ABOUT THE AUTHORS

Michael Dreyer received his doctorate in engineering in 1993 at the Centre for Applied Space Technology and Microgravity at the University of Bremen and has led their multiphase flow group since then. He is chairman of a French/German project on the behaviour of propellants in launcher tanks. His research is mainly funded by the German Aerospace Centre DLR and ESA. He is the principal investigator on the NASA/DLR experiment CCF. Dr. Dreyer is the editor-in-chief of Microgravity Science and Technology. He has published 2 books and co-authored 33 journal articles.

Ilia Roisman received his doctorate in mechanical engineering in 1998 at the Technion-Israeli Institute of Technology in Haifa. He is currently Privat Dozent at the chair of Fluid Mechanics and Aerodynamics at the Technische Universität Darmstadt and coordinator of the research area for near-wall multiphase flows at the Centre of Smart Interfaces. He has co-authored 1 book and about 20 journal articles.

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Bernhard Weingartner received his degree in theoretical physics at the Technical University of Vienna in Austria where he is working on his PhD at the Institute of Fluid Mechanics and Heat Transfer. With support from the Austrian Space Agency, future investigations are planned on the sensitivity to the ambient gas-phase conditions on thermocapillary flow. A corresponding study for the Japanese module Kibo will be a collaboration among European and Japanese scientists.

When a spray of water in your shower hits the wall, the result is something called an inertia-driven flow. It may look simple, but it’s not. For example, the spray impact also involves the transfer of heat from the spray to the wall. This exchange has a wide range of important applications from cooling high-power electronics on Earth to the design of spacecrafts, which also have to work in high-temperature extremes.

Because the hydrodynamics of inertia-driven flows on rigid walls is not completely understood, the influence of gravity on the outcome of spray impact is not clear. When spray hits a rigid wall, a thin, fluctuating liquid flow is created on its surface. This flow includes jets, sheets, crowns and capillary waves. In many cases the sheets are unstable and break up into secondary drops.

Any study of these fluid flows becomes even more difficult when spray strikes a very hot surface. For example, what happens when fuel is sprayed onto a piston in an internal combustion engine? If the piston’s surface temperature reaches a certain value higher than the boiling point of the liquid called the Leidenfrost point, the liquid doesn’t actually touch the surface. Instead, it evaporates beforehand, creating a thin vapour layer or wall between the piston and the liquid. This process leads to the explosive breakup of the liquid and the creation of secondary drops (see Figure 2), a phenomenon quite common when cooking. If water is sprinkled onto a skillet whose temperature is high enough, the water breaks up into droplets that skitter across the pan’s surface.

The thickness of the vapour wall created by spray impact is roughly 100 micrometers, and the typical duration of the event is about 10 microseconds, all of which makes the experimental examination of such flows rather demanding. However, in a microgravity environment these length and time scales can be expanded without altering the underlying physics. This permits the investigation of gravity’s effect on numerous outcomes including spray impact, the wall-film thickness, the dynamics of the splash and the heat transfer associated with the spray impact.

A single drop hitting a wall creates a relatively fast, radially expanding flow, which interacts with the stationary liquid film around the point of impact—think of raindrops hitting a puddle. Upon impact, liquid in the puddle rises in a sheet surrounding the drop’s entrance, forming what looks like a raised crater. The motion around its edges is governed by the surface tension of the liquid. A liquid rim forms on top of this raised crater, almost like the lip of a cup. In fact the velocity of the rising liquid sheet is faster than that of the rim on its upper edge; the rim continues to grow with the flow of liquid entering the rim from the sheet. If the rim lasts long enough before it collapses back onto the surface, then it becomes unstable and forms finger-like jets around its perimeter. When these become unstable, they pinch off into droplets. This is the physics behind what you see when pouring a glass of milk, and that last drop hits the liquid surface with a
splash resembling a crown. Those droplets pinched off the crown’s points are the secondary spray we know as splashing.

Now multiple drops hitting a puddle, as in a rainstorm, can complicate this ideal picture. Individual drop impacts may appear as described above, but if the drops land close to one another or in quick succession, then the symmetry of the interaction is broken and a liquid sheet may rise up between the two points of impact. In any case, these liquid sheets are less stable and may collapse earlier, often breaking up into jets and later secondary drops—or a lot of splashing.

Under microgravity conditions, the lifetime of the uprising liquid sheets may be much longer because gravity no longer pulls them down into the film’s surface. In such cases, the entire liquid rim may detach from the surface film and be suspended before it eventually breaks up into individual drops around its circumference. So, although there are an infinite number of scenarios of splash when a spray impacts a wall, they are composed of a few number of basic interactions that can be well described and predicted.

All this seems pretty esoteric, but inertia-driven flows have applications on Earth ranging from microelectronics to aircraft jet engines. By studying these flows in a microgravity environment, it will be possible to glean a greater understanding of the fundamental physics behind spray-flow patterns and droplet depositions on a surface.

**Bridges over Troubled Waters**

In an experiment conducted on the ISS in 2003, a thick film of pure water was produced by simply immersing a wire loop several centimetres in diameter into a beaker of water. This liquid film turned out to be remarkably resistant to surface deformations. It seemed like a straightforward discovery, but then something unexpected occurred.

Injecting tiny flakes of mica into the pure water allows any hidden flows and swirls to become visible. The ISS astronaut conducting the experiment observed that all motion within the film appeared to cease a few minutes after the experiment began. So he turned on a flashlight to have a better look. Suddenly the fluid started to move again—almost as if someone was stirring it with an invisible spoon.

The explanation for this surprising effect, known as thermocapillary flow, is not complicated. The focused beam of the flashlight heats the water film, thereby slightly lowering the sur-
face tension on the spot where the light shines. The resulting imbalance of surface tension drives a flow from the hot to the cold area and back again, resulting in the appearance of a “stirring” motion. Similar flows can also arise from variations in chemical concentrations or the presence of an electric field but experimentally, it is more revealing to generate a temperature variation. This ISS experiment could not have been done on Earth as the film would have immediately drained and collapsed. Under gravity only thin water films are possible, and they have to be stabilized by adding soap.

A good test for the systematic investigation of this thermocapillary flow involves the creation of a liquid bridge between the end walls of two cylindrical rods. Setting the rods at different temperatures leads to a temperature variation in the liquid, which results in a difference in surface tension along the outer surface of the liquid cylinder.

When the temperature difference is small, a steady vortex ring is established in which the rotating fluid takes on a toroid or doughnut shape. This ring consists of surface flow moving from the hot to the cold side of the outer surface and a return flow in the interior of the liquid bridge. Increasing the temperature difference above a certain threshold gives rise to flow patterns that vary with time. Adding tracer particles to the liquid reveals the flow.

Understanding liquid bridges has a very practical application in the electronics industry because at the heart of all electronics is a pure, single silicon crystal. It is produced by something called a floating-zone crystal-growth process. The purity of the crystal depends on the quality of the flow of melted silicon, and liquid-bridge science is the model for understanding how this all works.

The Hidden Organisation

In Earth’s gravitational field, water flows downhill, masking deeper dimensions inherent in the fluid itself. In a gravity-free environment, what we see is the hidden organisation of fluid dynamics that is a basic part of fundamental physics.

For example, under certain conditions in a liquid-bridge experiment, tracer particles accumulate and form a three-dimensional spiral string. Viewing it through the transparent top...
rod (a sapphire crystal), the particle accumulation structure (PAS) looks like a “windmill,” with three blades rotating at a constant speed. But the rotation is an illusion because the particles follow the flow, which is essentially toroidal. In fact it is the three-dimensional pattern that rotates, not the liquid, and the individual particles organize themselves into what appears to be a rotating wave (see Figure 3a). This separation from an initially homogeneous distribution of particles can be traced back to particle-free surface collisions, but as yet it is not fully understood.

Another interesting example of fluid flow self-organization appeared in the following simple experiment. A liquid is poured into an open container that is heated from below and cooled from above. Since the temperature varies perpendicular to the free surface, no surface-tension variation is initially present. However, if the temperature difference across the layer rises above a critical threshold, the onset of patterns that resemble biological cells can be observed (see Figure 3c). This is known as Marangoni instability and is triggered by the appearance of weak hot spots on the surface. A similar process can be detected at the surface of rapidly evaporating metallic paint, though in this case the cooling (and resulting temperature difference) is caused by evaporation.

Tears of Wine

Under terrestrial conditions, the thermocapillary effect described is usually masked by buoyant convection caused by the thermal expansion of the liquid. Both effects are connected because both are caused by temperature variations. In order to properly analyse the effect, it is essential to decouple the complex flow driven by the two forces (buoyancy and thermocapillary) and isolate the effect of each.

Experiments in microgravity offer the opportunity to learn more about thermocapillary effects, free from the influence of buoyancy. Purely buoyant flows, on the other hand, can be studied on Earth in closed containers where there is no liquid/gas interface. Experiments performed in both environments will make it possible to understand the processes of combined buoyant-thermocapillary flow.

Buoyancy forces are proportional to the volume of the liquid, while thermocapillary forces act solely on the liquid’s surface. If the system involved is very small, the importance of buoyancy diminishes. As a result, it is possible to observe small-scale thermocapillary effects on Earth. For example, this is why the oil in a hot frying pan always moves toward the cold rim and why a thin layer of wine can climb the side of a wine glass, accumulate at a certain height, form droplets, and subsequently flow back down the glass as “tears of wine.”

Thermocapillary flows also arise in an assortment of important space applications. As an example, heat pipes are important for cooling electronic devices in microgravity. At the hot end of the pipe, liquid evaporates and turns to vapour. The vapour then flows to the cold end of the pipe, where it condenses. The replenishment of liquid at the hot end is accomplished by the thermocapillary effect, which drives the condensed liquid towards the hot side of the pipe.

Another example is boiling liquids in weightless conditions. Intense thermocapillary flow arises near the point of contact where the hot solid wall, the cold liquid, and the evaporated gas meet. The powerful flow induced by the local surface-tension variation contributes significantly to heat flow.

Complex but Essential

Fluid physics is complicated but essential in our everyday lives. And as the 2008 incident at Heathrow Airport showed, it is of more than passing academic interest. Our knowledge of this science is generally good but incomplete. As the technology derived from fluid flows—high-pressure fuel pumps, silicon chip manufacturing, and server cooling systems—becomes more exacting, filling the gaps in our knowledge becomes more important.

While microgravity experiments provide indispensable details and proof of the phenomena, it is essential that they be accompanied by theoretical analyses, numerical simulations, and ground-based testing. Together, all these efforts permit a direct experimental comparison, which helps us understand the many processes involved in choking, capillary forces, thermocapillary flow, and other fluid motions.

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Breaking the Mould: Metallurgy in Microgravity
Factories floating in space? Not quite, but the next giant step in metal processing technology may come from an unexpected source: the ISS.

By Hans J. Fecht and Bernard Billia

We often think of breakthroughs such as artificial hips and knees and even dentures as modern day inventions. But these and millions of everyday products would not exist were it not for a process dating to the 1st millennium BC: casting. The processing of metallic alloys (a combination of two or more elemental metals) through melting and casting techniques, whereby the molten material is poured or forced into a mould and allowed to harden, was invented several thousand years ago. Today, this processing is still an important step in the industrial production chain for a wide range of products from the very simple to the highly complex: turbine blades for jet engines, low-emission engines for cars, so-called supermetals used to produce wafer-thin sheets for electronic components, high-performance magnets and fine metallic powders to catalyze chemical reactions, to name just a few.

Clearly, while the metallurgy done today owes a debt to history, the process itself has undergone much—ahem—refining. The end products often need to perform well and retain their integrity under extreme circumstances, particularly when used at high temperatures or when the product must be as light as possible in order to conserve energy. To produce these high-performance materials, the process must be closely controlled for the sake of both optimal design and efficiency of production.
Exactly how effectively this process is controlled means a great deal to the industry bottom line. Profits must be balanced against costs. The production and fabrication of alloys together with the casting and foundry industry generate a considerable amount of wealth. For example, the 10 million tons of castings produced in one year within the European Union is worth about 20 billion Euros. To continue generating this kind of turnover, the casting and foundry industry relies on the design and creation of advanced materials, which is accomplished by using sophisticated computer codes to control the metallurgical processes.

Although the industry does its job very well, competition is fierce, and everyone is always looking for the next great breakthrough, that leap forward in technology that revolutionizes the way business is done. The answer may lie in a surprising place: space. A scientific pro-

**FIGURE 1. DENDRITE GROWTH**

On the left, 1a shows the tree-like dendrite growth of a metal alloy in column-like formations. On the right, 1b is a computer-generated image of dendrite microstructures. Dendrites are in blue, and they crystallise before the liquid portion of the melt, shown in green and red, solidifies.

**FIGURE 2. ENGINE COOLING**

Filling simulation and temperature distribution for a car engine block using Magmasoft computer simulations. In this image, the yellow areas are hot, the blue ones are cooler.
gramme established by ESA using weightlessness as an important research tool on parabolic flights, on sounding rockets and, in the near future, on the International Space Station.

The idea of casting metal in space probably seems at best outlandish and at worst unnecessary. Why should microgravity be an important research tool when previous success has been achieved using ground-based, gravity-conditioned methods? To find that answer we need to look further into the melting and casting process.

Metal Works
As previously stated, casting is a process by which a molten metal is solidified. The liquid-to-solid transition is driven by the properties of hot liquid metal and the way in which it cools over time, in the same way that water freezes to ice at 0°C. From the standpoint of physics, castings belong to systems in which, rather than changing evenly in space and smoothly in time, the solid phase normally forms unevenly and with diverse microstructures (see Figure 1).

Sophisticated computer models have been developed within the past 10 years that allow the formation of such microstructures to be analysed in great detail. For example, Figure 1b shows the evolution of the tree-like structures called dendrites (blue), which crystallise before the still-liquid portion finally solidifies (green and red; see also “Dendrite Formation,” right). This interaction between experiments and computer simulation has led to improved designs as well as improved performance undreamed of in the past.

The fact that the transition from liquid to solid state is not a uniform process holds true whether one views the finished piece at the smallest increment (nanometre) or on the largest scale. In addition, the rate at which a casting cools affects its microstructure, quality and properties. Generally, the areas that cool quickly have a fine grain structure while the areas that cool slowly have a coarse grain structure. Figure 2 illustrates the temperature distribution within a car’s engine block immediately after the casting process was finished. Here we see that the temperature varies considerably between different locations within this large piece of metal since cooling occurs at a much higher rate close to the interface with the mould. It follows that for high-precision castings, the mastering of the grain structure during the liquid-to-solid phase transition is paramount for quality control as well as the engineering, tailoring, and design of advanced materials for specific technological applications.

Cast in a Different Mould
It seems an amazing contradiction that despite the array of complex products currently manufactured, much of the basic physics behind these processes remains poorly understood. Clearly, the demands of industry call for the continued improvement of materials processing in the areas of composition, microstructure and performance by:

- Determining the thermophysical and related properties of metallic melts
- Mapping out basic relationships between alloy and mould at the microstructure level
- Developing predictive modelling of the formation of grain structures during solidification.

Dendrite Formation

Named after the Greek word “dendron” for tree, the term dendrite applies to a wide variety of structures with tree-like branches such as neurons, which are composed of a cell body and dendrites that extend from that body. Snowflakes, which exhibit an infinite number of elegantly shaped branches with hexagonal symmetry, are the most familiar example of dendrites. After water vapour forms and solidifies on a tiny dust particle (nucleation), the arms of the snowflake branch out directly from the newly formed ice crystal.

Their complex shape continues to evolve as a result of infinite variations in conditions such as temperature, humidity and chemicals encountered by each ice crystal as it falls through the atmosphere. Most snowflakes begin as relatively flat, hexagonal shapes. The level of complexity of the dendritic arms results from the instability of these smooth shapes and their reaction to the changing environment. In images (a) and (b) below, the six dendritic branches are basically identical to one another, which indicates that the growth conditions were similar around the growing crystal. If the arms were asymmetrical, however, this would indicate that the conditions surrounding one branch were slightly different from those of its neighbour. For comparison, image (c) shows snowflake-like grains growing in a melt.
Looking up: Europe's Quiet Revolution in Microgravity Research

Accomplishing these tasks requires benchmark data, and experiments performed in microgravity enable the study of the above properties free of certain restrictions of a gravity-based environment. In space it is possible to suppress gravity’s effects on the flow of molten metals and on sedimentation during solidification. Without gravity’s interference, it is possible to isolate other properties for investigation, such as diffusion and how it contributes to mass and heat transport in the melt without the gravity-associated complications of certain solute ingredients being more buoyant than others. Under normal circumstances, the transfer of heat is modified by convection in the melt, a process that makes portions of the melt “float” or “settle.” Solid grains most often settle under the opposing forces of weight and buoyancy, which is called sedimentation. Obtaining evidence of this behaviour through real-time x-ray studies on the ISS is one of the primary goals of experimentation.

The resulting insights into alloy solidification and processing to be gained can potentially be used to produce new and unique microstructures. In addition, the space environment allows levitated melts (see “Electromagnetic Levitator” on opposite page) to be controlled effectively at temperatures up to 2000°C. This control enables the critical parameters of the liquid to be measured much more accurately than in an Earth-bound laboratory. Monitoring these experiments with sophisticated computer equipment has lead to improved validation of predictive models of this process—information that was much needed.

Research by Levitation

So the idea of taking a process thousands of years old and experimenting on it in space under weightless conditions is not so crazy after all. However, it is still necessary to consider what research can and should be carried out. ESA’s research programme focuses on a number of areas, including alloy solidification when there are multiple phases and components, such as the multicomponent alloys used in many products, including the non-iron alloys used in jet engines and the growth of semiconductors such as silicon for solar-powered cells.

In order to perform the necessary experiments, it is important to have access to extended periods of reduced gravity. Microgravity experiments in materials research conducted by ESA are to be carried out in a number of multi-user facilities onboard the ISS, as well as on other microgravity platforms, such as parabolic flights and sounding rockets. One ISS facility important to the field of materials research is the Materials Science Laboratory (MSL). The MSL’s furnace inserts allow highly specialized solidification experiments to be performed under microgravity conditions, with and without the application of flow-inducing magnetic fields.

Another crucial ISS facility is the Electromagnetic Levitator (EML). As fantastic as it sounds, this equipment does precisely what the name implies: levitates molten metals. The EML permits containerless melting and solidification of alloys and semiconductor samples. Furthermore, the EML is equipped with highly advanced diagnostic tools that permit accurate measurements of thermophysical properties, as well as direct observation of the experiment during flight by high-speed videography.

Using such advanced techniques to gather data on the intricate processes of melting and casting brings us closer to the design of new materials with better performance. Such advanced products can range from metre-sized objects to micrometer-sized powders, for example:

- energy efficient engines for the car industry
- metallic foams
- medical implants

Using such advanced techniques to gather data on the intricate processes of melting and casting brings us closer to the design of new materials with better performance.
• powder production to improve catalytic performance of modern fuel cells and advanced combustion engines
• silicon-based materials for improved solar cells
• precision casting of detailed shapes and micro-thin sheets
• materials for high performance magnets and
• low-weight and high-strength materials for modern space vehicles within the space exploration programmes.

Intermetallics: Not a Space-Age Rock Group
A new international European Commission-Integrated Project (with ESA) has been established in the field of intermetallic alloy solidification. Christened IMPRESS—Intermetallic Materials Processing in Relation to Earth and Space Solidification—this project represents an important step toward promoting scientific reciprocity between ground-based and microgravity experiments. The project comprises about 40 industrial and academic research groups from 15 European countries and will increase our understanding of the critical link between materials processing, structure, and final properties of new intermetallic alloys, such as TiAl (titanium aluminide) and NiAl (nickel aluminide). For additional information, see the IMPRESS website at ESA http://www.spaceflight.esa.int/impress/.

Called “aluminide intermetallics,” these aluminium-based alloys have a definite proportion of two or more elemental metals and have many attractive mechanical, physical and chemical properties due to their crystal structures and strong chemical bonds. For example, Ti-aluminides are well suited for blades in high performance aircraft engine turbines because of their reduced weight, improved mechanical strength and resistance to damage from stress whereas powders of Ni-aluminides have excellent catalytic activity for fuel cell applications. In both cases the use of these advanced materials improves the system performance tremendously.

Melting Away the Barriers
As the products we make become more sophisticated, it follows that their production processes must keep up. Advancements in liquid processing techniques have enabled industry to create products such as jet engines, medical implants and spacecraft, but society’s push for continually stronger, lighter and more efficient products requires that next great leap.

The most recent developments in technologies have been seen in liquid processing, which has the potential to improve the facilities responsible for the casting of complex parts and production of powders for the catalytic activation of chemical reactions. To make this process more reliable, sophisticated computer models have been recently introduced in which all aspects of industrial liquid metals processing are standardized to ensure long-term sustainability. To keep moving forward, ESA, together with the European national space agencies, has set up a scientific programme using the unique, gravity-free environment on parabolic flights, sounding rockets and, in the near future, the ISS to develop new designs, structures and products.
Shake, Rattle and Roll: Using Vibrations as Gravity

In space, you can’t toast your successes with Champagne or sweep sand into a pile to clean up. So how can you make matter behave?

By Daniel Beysens, Pierre Evesque and Yves Garrabos

We have all seen television footage of astronauts floating around on Mir and the International Space Station. Freed from Earth’s gravity, they move weightlessly in a slow-motion ballet, unrestricted by “up” or “down.” But what do we know of the effects of weightlessness on the behaviour of inanimate matter such as liquids, gases and granular matter such as sand? On Earth we take for granted that liquids sit at the bottom of the bottle, gas mostly rises to the top and grains naturally stick together to form sand piles. When weightless, it is not possible to pour yourself a glass of Champagne—the liquid won’t drop to the bottom—and even if you succeeded, the bubbles would just sit in the liquid and wouldn’t rise to the top. Nor could you build a sand castle. The grains of sand have no attraction between them, called cohesion, to keep them together; and thus spread like gas molecules in the air.

***AT A GLANCE***

- Vibrations can act like artificial gravity on inanimate matter.
- Behaviours of liquids and gases including heat transfer, condensation and evaporation must be controlled for efficient use on spacecraft.
- Granular matter can act like a solid, liquid or gas and the role of vibration on its properties must be better understood.

—The Editors
Modelling Matter

The picture this presents is one of chaos. Clearly human beings can direct their movements under these conditions, but are they left to swim through a sea of floating debris? More importantly, how does the spacecraft itself function? Fortunately there are forces other than gravity at work. Although gas bubbles, liquid droplets and solid objects are no longer subject to the rules of gravity, they are, however, still bound by inertia—that is they remain at rest until and unless some force exerts pressure on them.

That force can be quite minimal—in the form of vibrations. Even a weak vibration in space causes matter to feel the stress of that pressure and to respond with an equal reaction, such as a counter movement. As illustrated in the experiments discussed below, these reactions often mirror those like buoyancy that you would expect on Earth where gravity is present. Thus, the vibration acts as an artificial form of gravity.

Fluids provide a good model for investigation when they are under the specific conditions that correspond to their “critical point,” which occurs when pressure and temperature become high enough so that liquid and gas can no longer coexist. Thus, the boundary between the liquid and gas phases disappears. The two states mix together as a dense gas (a gas with the density of a liquid) and are called “supercritical fluids.” For carbon dioxide, the critical point occurs at a temperature of 31°C and pressure of 73 bar, which is 73 times the atmospheric pressure. For water, the critical point pressure is 220 bar and temperature is 374°C. When near their critical point, all fluids behave in a similar manner; so by studying one fluid, the properties of all fluids can be deduced, a phenomenon called “critical point universality.” (Kenneth G. Wilson won the Nobel Prize in 1982 for providing the theoretical framework to estimate the universal features of critical point phenomena.)

Supercritical fluids possess other interesting properties, for instance supercritical carbon dioxide is a very powerful solvent of organic matter and it is not harmful to living things or the
environment. It is also possible to burn dangerous wastes, like ammunitions, in supercritical water efficiently and safely. Fluids like oxygen and hydrogen are also used in space under supercritical conditions because they remain homogeneous regardless of the spacecraft’s accelerations—or absence of accelerations—and the orientation of the gravity vector.

Supercritical fluids are very unstable and particularly sensitive to the effects of gravity or vibrations. This property and the fact they are universal models for fluid behavior makes the observation of their behaviour extremely helpful. Sand fits these criteria as well in that the grains can act like molecules of a liquid or gas depending on the situation.

**Being Hot is “Cool”**

As anyone who has ever made pasta knows, when a liquid in a saucepan is heated from below and before the liquid boils or the pasta is added, the layer closest to the heat becomes lighter than its environment and rises. As it cools down at the top, it sinks down and a rapid ordered motion develops creating a circulatory pattern of rolls within the liquid, thus transferring the heat throughout, which is called convection. This behaviour can also be seen with gases, in which, for instance, cyclic clouds are quite often observed.

Since microgravity removes any semblance of up and down, you would expect to see an altogether different pattern of motion when a liquid is heated in space. However, we can reproduce the convection pattern using vibrations as artificial gravity. When a container and its contents are heated and then vibrated, the pattern of motion resembles that seen here on Earth. This behaviour can also be seen with gases, in which, for instance, cyclic clouds are quite often observed.

Due to the lack of experimental time in space, the stripes shown in Figure 2 are not the ultimate equilibrium state, which we expect to be a unique vapour stripe in the middle of the cell as parallel—to the vibration, but this reaction can be explained by the fact that other forces are triggered by the vibration force.

**The Converts: Condensation and Evaporation**

We’ve all—quite innocently, of course—fogged up the car windows at some point. Under these normal conditions on Earth, when a fluid starts to condense, tiny liquid droplets form and these tiny droplets fuse and run together to form larger ones. Because liquid is the heavier substance, gravity causes it to pool together under the vapour, and the boundary between the liquid and gas phases is flat (see Figure 2a).

Under weightless conditions, however, bubbles or droplets can only grow by the haphazard and slower process of collision, known as diffusion. What we are left with is a strange-looking mixture: in the liquid there are a few large vapour bubbles that coexist with many tiny vapour bubbles. In addition, the appearance of the mixture varies according to the vapour volume. When the vapour volume is greater than 30% of the fluid, the bubbles are so close together that it forms an interconnected pattern (see Figure 2c). When the vapour volume is less than 30% of the fluid, we see that the boundary between liquid and vapour is spherical (see Figure 2b), unlike the flat surface seen on Earth.

In one experiment, we initiated the evaporation of a liquid under low amplitude, high frequency vibrations (200 µm, 20 Hz). Under these conditions, the vapour bubbles progressively align and stretch and fuse together. Then, rather surprisingly, stripes of gas form in space in a way that remind you of the flat interface between vapour and liquid which we see on Earth (see Figure 2d–i).

Due to the lack of experimental time in space, the stripes shown in Figure 2 are not the ultimate equilibrium state, which we expect to be a unique vapour stripe in the middle of the cell as
Is Sand a Fluid?
Sand is a model for other granular matter. Its study in the weightless conditions of space raises numerous technical issues, such as the best way to work with grains and powders in satellites and spacecraft. (Indeed, when travelling for 20 years we will need to grow plants, to cut them in pieces, to harvest corns and seeds, to grind or sow them to get food, and so on.) Such studies may also answer very fundamental questions concerning the formation of asteroids and the history of the Earth’s formation. At the same time we need to ask: “Should we consider granular matter as a gas or a liquid or a solid, since on Earth sand can flow like liquid and form sand piles like a solid and, in weightless conditions, can float and spread around like a gas?”

In this context, grains act like fluid molecules. Will they also exhibit properties of various states of matter: gas, liquid and solid?

However, in order to be considered as either a fluid or a solid, sand must exhibit a “temperature.” What does “temperature” look like? In a fluid, temperature is achieved by the random motion of molecules: the higher their velocity, the higher the temperature. Thus, in terms of sand, the grains would acquire a temperature by reaching a random velocity, and that motion would generate energy known as kinetic energy. One way to create motion is by vibrating the walls of the sand container, so that the grains near the wall will collide, and then continue to collide with other grains. In this way grains behave like the balls struck on a snooker table.

Unfortunately, during the series of collisions, some energy is lost or dissipated, which is why vibrated granular matter is often called “dissipative matter.” Scientists are using weightlessness to address the different forms of energy found in this strange “dissipative” matter and to determine its characteristics. These studies are still in their infancy. However, in experiments carried out on Earth, it turns out that the main physical parameter that determines sand’s behaviour is the number of layers of grain in the experiment container. This finding makes the properties of granular matter very abnormal, as these properties change when the volume of matter is changed. Temperature is one example of such a property. As stated above, temperature is determined by the velocity of the grains,
which is created through collisions. Because a small amount of velocity is lost by dissipation, the grains in the center of the container will have a velocity lower than the grains near the vibrating wall. Thus, granular matter consisting of many grains will be cooler at its centre in contrast to matter consisting of only a few grains that exhibit nearly the same velocity.

In-Grained Behaviour
To illustrate this phenomenon, we first apply vibrations to only one grain in a rectangular box. On Earth—where the properties such as gravity and friction apply—our one grain can only collide with one wall. In space, however, not only does the one grain bounce between two walls, it also rebounds in a perfectly perpendicular straight line. This obviously does not happen on Earth where the grain does not reach the second wall but moves along by “jumping.”

The center image in Figure 3 is an illustration of two coherent grains moving at the same speed in a vibrated experiment container under weightless conditions. The reason that the grain bounces from wall to wall in a straight line is because it does not rotate. Think again of the snooker table. A player can strike the cue ball off-centre to impart “spin” and affect the movement of the ball using the rotation of that spin. But in this experiment, there is no spin.

The reason the grain does not rotate or “spin” is related to the shape of the container (a cube or a cylinder, chosen for sake of simplicity) and to the friction that results when a particle with an inclined trajectory rebounds with some rotation on one surface and with the counter-rotation on a second surface. As energy dissipates in the collision, the grain speed after the rebound is less than before, a decrease that eventually “freezes” the grain rotation. What is also remarkable is that the grain moves at a much faster speed than the vibrations of the wall—a paradox when one considers the energy lost during each collision with the walls.

Multi-Grain
If one performs the experiment with two grains of the same size, both particles move at the same speed. Can this coherent motion be applied to more grains in such a way that they form a

**FIGURE 3.** On the Rebound

The behaviour of sand grains subjected to vibrations, indicated by the double red arrow.

Left: On Earth, the vibration is too weak for the grain to overcome gravity and reach the second wall. Thus it moves forward by “jumping.” Centre: Under weightless conditions two coherent grains move at the same speed in the vibrated container. Both particles collide only with the walls and make one round-trip per vibration period. Right: With many grains in the container, the grains collide with the walls and with each other. Higher grain density in the middle of the cell means that they cannot move as fast there, which also means the temperature is cooler there than along the sides where they move more freely.
“grain laser” in which a continuous stream of sand grains is emitted like photons of light beaming from within a laser? Unfortunately, when we increase the number of grains, they start interacting strongly, colliding and repelling each other as they cannot occupy the same place at the same time. The motion loses its coherence and becomes erratic.

With many grains in an experiment container, the trajectories of those grains are then complicated by collisions (see Figure 3). If the grain concentration remains relatively small, the grains uniformly occupy most of the available space (the container length minus the zone where the wall vibrates). If we increase the concentration of the grains past a certain point, they generate a cloud of gas.

However, the system is not completely random. The grains do follow certain behaviour patterns endemic to a liquid or gas. As discussed previously, the grains acquire temperature through movement, which creates kinetic energy. The distribution of speeds within the experiment container can vary considerably, and even the thickness of the container can make a difference. Grains no longer have the same velocity (or temperature) everywhere. Slower speeds in the middle of the container mean cooler temperatures while faster speeds along the top and bottom lead to hotter temperatures.

### Behaviour Matters

Obviously, scientists’ chief concern in studying these behaviours is not to make it possible to build sand castles—or drink Champagne. Liquids and gases are essential to the functioning of spacecraft and to life support systems, but the weightless conditions in space make it quite difficult to use them efficiently. We have found that vibrations can play the role of artificial gravity for a number of key phenomena specific to the behaviour of liquids and gases, such as thermal convection, evaporation and condensation. Hot and cold fluid, bubbles and droplets find a respective “up” and “down” when the vibration is turned on, thus simulating a reaction like that seen under normal gravitational conditions. As a matter of fact, physicians are already using vibration as artificial gravity to prevent muscle decay or bone decalcification in space.

Granular matter (sand), although often considered regular solid matter, exhibits unique behaviours and properties, some of which are still unknown. As we have seen, the individual grains act similarly to the molecules of a liquid or gas. As such, vibration gives them a velocity and a “temperature.” The behaviour of granular matter in space will be understood when the nature of this temperature and the role of vibration are better understood. Once the right conditions are determined and then applied, we could theoretically affect the behaviour of grains so that they cohere as a solid, flow as a liquid, or expand as a gas depending on their intended use. It is both a fundamental problem that is related to the origin of the universe and the formation of dust, asteroids and planets and, more practically, it is quite essential for astronauts as it relates to the everyday necessities of growing food, managing waste and, in a word, surviving during long-duration journey through the universe.
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The 1993 discovery that complex plasma can exist as soft matter changed the face of physics. Since then, research into its properties and behaviours has exploded, and experiments on the ISS have led to a number of discoveries that could not have been made in the presence of gravity.

By Gregor Morfill and Hubertus Thomas

Rarely is a scientist able to announce the discovery of a major new state of matter; in particular a state that common sense suggests should not exist. But this is precisely what happened at the International Conference on Phenomena in Ionised Gases in September 1993 in Bochum, Germany.

A Different State of Matter
Matter exists in four states: solid, liquid, gaseous, and plasma. It might be argued that plasma is nothing more than the ionized or charged state of gas. However, since the physics of interactions within plasma and gas is very different, the consensus is that plasma should be regarded as the fourth state of matter. This simple picture corresponds to the old elements of Earth, Water, Air, and Fire, but it is not the whole story.

In the late 20th century, the Nobel laureate Pierre-Gilles de Gennes coined the term “soft matter” for a class of large (centimetre-sized) assemblies of substances that appear “soft” and consist of various supramolecular or “large” entities (large by atomic or molecular standards). He defined soft matter as “supramolecular substances, which exhibit special properties such as softness or elasticity, which have an internal equilibrium structure that is sensitive to external forces, which may possess excited metastable states, and where the relevant physics occurs far above the quantum limit.”
Traditionally, matter exists as a solid, liquid, gas or plasma, but complex plasmas or soft matter can be created by adding large or supramolecular particles to ordinary plasma.

Studying soft plasma matter on Earth is difficult because it must be levitated to be viewed, and gravity pulls it downward.

Experiments in space have resulted in supercoagulation in a neutral gas, which formed one giant conglomerate and a range of smaller ones.

Complex plasma research can be applied to many areas: waste removal, pollution control, solar cells, semiconductor chips and medicine.

—The Editors
Soft matter comes in two different states. Granular solids, polymers (compounds made up of large molecules) and foams represent the solid state, while emulsions and colloids (mixtures containing particles of one compound suspended in another, milk is one example) represent liquids. The 1993 announcement in Bochum that supramolecular or complex plasmas could be made to assume crystalline structures caused quite a stir. Sir John Maddox, the editor of *Nature* at the time, reflected the opinion of the day when he stated:

“That physicists are the masters of artifice in the experiments they design is widely recognised, but sometimes their tricks quite take the breath away. Most of what follows is about an experiment of outstanding ingenuity, which, despite the electronic equipment no doubt accompanying it, is also simple. The word ‘elegant’ is overworked, but in this case it applies…”

Maddox concluded his discussion of soft matter by stating: “What the authors themselves would like to do is to carry out their experiment in microgravity conditions. On the face of things, it is a more deserving candidate for room in some future Space Shuttle flight than most of the others so far suggested.”

**Complex Plasmas**

Plasma is everywhere, though it often goes unrecognized. The mammoth strike of a lightning bolt and the tiny sparks of static electricity are both examples of plasma. The Sun is a huge ball of plasma; in fact plasma is quite common in space. On Earth, plasma has multiple uses in many industrial applications from lights to plasma televisions. Ordinary plasma is a collection of particles: positively charged ions (electrically charged atoms) and negatively charged electrons. The system’s charge is neutral; in other words, there are as many positive as negative charges. The particles interact via their electric forces instead of through atomic or molecular interactions, as is the case in neutral gases. The discharge that produces light in mercury- or sodium-vapour streetlamps is an example of ordinary plasma in action.

Complex plasma has an additional component—charged supramolecular microparticles (see Figure 1). Although these microparticles can be as small as one ten-millionth of a metre, they are extremely heavy—many billions of times heavier than atoms—and still carry a charge. In fact if their number is sufficiently large, they become the dominant component and as such will determine the structure of the system. This can happen in an interstellar gas cloud when the addition of dust to the ordinary plasma present in the cloud turns it into complex plasma.

Because supramolecular microparticles have significant mass, changes in their state or motion are slowed by a factor of between one hundred thousand and one million, which means that individual particles can be seen. Hence the physical processes taking place can be viewed in super-slow motion and at the individual particle level. It’s an experimenter’s dream or, perhaps, a theoretician’s nightmare.

Being able to observe individual microparticles and their super-slow motion may be ideal for experimental studies of the strong and weak coupling phenomena (the interaction between particles) in multi-particle physics. This, in turn, could lead to a better understanding of the fundamental principles that govern the stability and self-organisation of condensed matter and of critical phenomena such as phase transitions (regular changes in state), as well as the explo-

**FIGURE 1. PLASMA PARTICLES**

An electron microscope image of typical particles used in complex plasma experiments. The particles are usually melamine formaldehyde and all are the same size, though occasionally metal-coated, needle-shaped particles have been used.
ration of the onset of cooperative phenomena—
phenomena that appear only when a large
number of elements act together to produce ef-
fects not predictable from the properties of their
individual components.

To perform these observations on Earth, a
device containing an upper and lower electrode
creates an electrostatic force that levitates the
microparticles and neutralizes gravity (see Fig-
ure 2). But Earth’s gravity is so strong that the
electrostatic force can create only a thin, hori-
zontal layer of free-floating microparticles. As
a result, Earth-bound experiments have natu-
really concentrated on flat or monolayer systems
(a single continuous layer that is only one micro-
particle, molecule, or atom thick). Still, these
are of great interest in many areas including the
study of surface physics, membranes and the
stability principles of condensed matter.

In the absence of gravity, however, the micro-
particles can occupy the whole plasma, and it’s
possible to obtain experimental conditions when
the system is isotropic (uniform), homogeneous
and not stressed by the pull of gravity. For the
precise measurements needed to study three-di-
mensional systems and for stress-free processes,
microgravity experiments are essential.

**Microparticles:**
**Charging and Shielding**

Generally, a microparticle introduced into plas-
ma will absorb electrons and ions and become
charged. In low-temperature plasma, the charge
on the microparticles is negative because elec-
trons are much faster than ions, and conse-
quently electron impacts occur more frequently
than ion impacts. The negative charge on the
microparticles repels the (negative) electrons
and attracts the (positive) ions. This continues
until, after a few microseconds, the collision
rates are the same, and the microparticle has
reached Q, its equilibrium charge (typically a
few thousand electrons).

Around the microparticle the free electrons
and ions react to its electric field and form a pos-
itive-charge cloud. The extent of this “shielding
cloud” (so named because it effectively screens
or shields the local charge of the microparticle)

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**FIGURE 2. PLASMA DISCHARGE DEVICE**
The most common device used in complex plasma experiments is a radio frequency (rf) discharge de-
vice seen here. The plasma is usually a noble gas (argon, neon) at a pressure of about 1 mbar. The
plasma is “ignited” using a radio frequency signal on the two paral-
lel electrodes. The microparticles are illuminated by a laser and
viewed by recording the reflected light with a CCD camera. Using a
thin (100 µm) sheet of laser light allows the simultaneous recording
of a whole lattice plane.

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**FIGURE 3. RAISE THE SHIELDS**
The shape of the plasma shielding cloud around a negatively charged
microparticle in (a) a uniform plasma distribution and (b) flowing plasma.
is called its “Debye length,” named after the famous Dutch physicist Peter Debye.

In isotropic plasma, where the plasma’s properties do not vary with direction, the shielding cloud is spherical. If the plasma flows around the microparticle, the shielding cloud is elongated and anisotropic, with an excess positive charge downstream. This occurs in complex plasma experiments conducted on Earth (see Figure 3).

The force between the microparticles is electric and, due to the shielding, has a limited range. If the particles are too far apart, they will be out of range and the system is said to be “weakly interacting.” In nature—in star-forming gas clouds, zodiacal light (sunlight reflected by a myriad of particles), planetary rings, lightning and so on—this is usually the case where complex or dusty plasmas exist.

However, if the particles are close enough, then the motion of each directly influences the motion of its neighbour, and they become strongly interacting. This presupposes that other forces, such as particle interactions with any neutral gas that happens to be present, are not more important. So for a description of strongly coupled complex plasmas, two parameters are needed: one describing the coupling strength and the other the particle separation.

**Human vs. Robot**

As suggested by Sir John Maddox, experiments on complex plasmas have been conducted in space, though in the two complex-plasma laboratories on the International Space Station rather than the Space Shuttle. From 2001 to 2005, the first lab was the Russian-German Plasma Kristall Experiment (PKE-Nefedov, named for the Russian project scientist who died just before the lab was installed on the ISS). The improved next-generation laboratory, PK-3 Plus, was launched in 2005 and was built on the same principles as its predecessor but with a more advanced design, better manipulation capabilities and improved particle and plasma diagnostics. A brief snapshot of experimental results from research performed on the ISS is summarized in “Experimental Results” on the opposite page.

While the decision to build the ISS was a political one, its ability to host complex research is a practical consequence. The presence of astronauts is a bonus, especially for the type of experiments that cannot be fully tested on Earth. By designing the instruments so that astronauts can perform the experiments themselves—exploring parameters that may be ideal in microgravity but impossible on Earth—the risks that always plague purely robotic missions can be reduced. Such research, performed with dedicated, versatile, space-proven equipment—little “laboratories” that can be reconfigured and adapted to study unexpected results and discoveries—can yield a great deal of new knowledge at comparatively little extra cost. Astronaut operation of the experiments has proven immensely valuable and has resulted in about 50 scientific publications. Of those publications, two exemplify the benefit of a living, breathing and thinking human experimenter over a robotic one.

**Supercoagulation**

The first is the discovery of “supercoagulation.” Cosmonaut Yuri Baturin conducted a series of
Experimental Results

Supramolecular substances. In this image the three states of complex plasma are revealed. Each white dot is a microparticle illuminated by laser light and recorded on camera. In the crystalline state, the microparticles occupy a well-defined, ordered lattice. In the liquid state, structural disorder and somewhat higher particle mobility is seen. In the gaseous state, the particles move much faster, leaving long tracks captured during a single exposure.

Elastic deformation. This set of images, taken from a video recording, was acquired during an experiment conducted on the ISS. The complex plasma cloud is initially deformed and then reforms elastically; the time scale was approximately one second.

Excited states. This slice through a 3-D plasma crystal was obtained in a laboratory on Earth. The ground state (the lowest level of crystal energy) exhibits a face-centred cubic (fcc) structure or a body-centred cubic. One can also see regions where the local structure is in an energetically excited, hexagonal, close-packed (hcp) state. Red indicates an fcc structure, green an hcp structure.

Response to external fields. These three images, obtained on the ISS, show the same liquid plasma under different external alternating current electric fields. The fields applied were (from left to right) 10, 12 and 19 volts. At the higher voltages the particles align along the field—a physical process similar to electrorheology (electrically induced deformation and flow) in colloids, albeit at a much lower voltage and frequency.

All these experiments were carried out at temperatures (typically room temperature) when the thermal energies were much higher than those of the quantum states themselves.

These examples illustrate that the strong coupling possible in complex plasmas leads to only one conclusion—the presence of the plasma state of soft matter. The fact that complex plasma can exist in solid, liquid and gaseous forms makes the complexity of these systems even more apparent. Hence the hierarchy of system states shown below begins to resemble the classical states of matter (solid, liquid, gaseous, plasma) — albeit with much more diversity.
experiments for which the methodology differed from the way they had been designed and programmed. The original idea was to perform a plasma experiment, but the plasma was never activated. So as an alternative, microparticles were injected into neutral, argon gas. The result was unexpected: no plasma and no charge. Instead, within seconds the microparticles formed one very large conglomerate and a whole spectrum of smaller ones (see Figure 4).

This result had two surprising features. First, the large conglomerate contained some 100,000 microparticles, whereas the predicted coagulation was just two particles. Second, the size spectrum of the smaller conglomerates was a power law. In physics, this is usually an indication that a special “scale-free” process is operating, meaning that the size of the conglomerate is not dependent on the energy of the particles. It’s unlikely such a discovery could have been made on Earth, because in a gravitational field the particles would have simply fallen out of view in a fraction of a second.

This discovery may have some interesting applications—in toxic waste removal, pollution control and industrial production processes. So understanding the origin of this behaviour is of considerable interest beyond the simple intellectual puzzle of why and how nature can create something 100,000 times faster than predicted.

When a theory emerged based on the initial experiments, the versatility of the PKE-laboratory and the human researchers made possible a series of subsequent experiments that confirmed the origin of this new physical process now called supercoagulation.

**Electrorheology**

Another example proving human superiority to robots involves “electrorheology,” an electrical-
Electrorheology is the process by which an external electric field is applied across a colloid fluid and causes major changes in the properties of the fluid by rearranging the suspended particles—in other words altering its structure, or rheology. Viscosity is modified, compressibility is changed and the shear modulus (the ratio of the shear stress to the shear strain) is altered. The fluid may even assume solid structure. This happens because the electric field induces a dipole in the (usually electro-active) colloidal particles. These induced dipole fields lead to a rearrangement and realignment of the particles, which in turn leads to changes in the fluid’s properties. The whole process works because the suspended particles are electro-active and the fluid is neutral. Interestingly, this property of colloidal fluids could be employed in everything from shock absorbers to the protection of buildings against earthquake damage.

The question arose as to whether complex plasmas might also have electrorheological properties. In other words, if “electrorheological plasmas” could be produced in a similar way as “electrorheological fluids.” This seemed unlikely as the conditions between the two systems could not be more different. In colloidal or complex fluids the background fluid is neutral and the particles within are electrically active, while in complex plasmas the background ion–electron plasma is highly conductive and the microparticles are insulators. In complex fluids the typical particle separation is approximately the particle size (in other words they are densely packed); in complex plasmas the particle separation is roughly 50 to 100 times the particle size.

Coagulation—the process of two or more particles joining together—requires that the particles touch and the cohesive (binding) forces overcome any elastic (repulsive) processes that would make the particles “bounce off” each other.

Numerous experiments have shown that the ability of particles to stick to each other depends on their surface material and collision dynamics. For instance, it is much harder to get rubber balls to stick together than snowflakes. But when microparticles were injected into neutral gas and a coagulation rate 100,000 times faster than predicted (based on geometrical–collision estimates) was achieved, the results presented a challenge.

It turned out that the particles injected into the neutral gas were charged: some positive, some negative. Thus, in addition to all the other cohesive forces, there was an electrostatic attraction as well as an induced-dipole attraction (two equal but opposite charges). The resulting new theory predicted that below a critical level of particle density, there should be no supercoagulation and no power law in the distribution of the size of particles. Subsequent tests carried out at lower levels of particles confirmed this.

This is a perfect example of how the classical scientific method works. A rapid coagulation (supercoagulation) process was observed in experiments carried out on the ISS, a theoretical explanation was developed, and its predictions were confirmed with further space-based experiments.

Results validated that adaptable human experimenters onboard the ISS are critical for following up on the basic experiments operated in “robotic mode” with available equipment.

This sequence shows the process of coagulation by consecutive sticking of particles in slow (non-destructive) collisions.

Supercoagulation
Nevertheless, theory predicted that an electrorheological process might exist for complex plasmas, too. Testing the theory on the ISS required an experiment that the equipment in the PK laboratory was not designed to accommodate. The hope was to observe “something”—perhaps the ordering of a normal fluid-like state into a string fluid, where the molecules are arranged in loosely coupled chains of various lengths along a given direction. A string fluid induces dramatic changes in the fluid’s physical properties, a change that can be exploited in, among other things, shock absorbers.

Of course, just in case the predictions were at least close, the cosmonauts needed to generate three-dimensional scans through the complex plasma and provide the greatest amount of diagnostic results possible (see Figure 5). The results ultimately confirmed the new theory and, in the process, validated the notion that adaptable human experimenters onboard the ISS are critical for following up basic experiments operated in a predetermined “robotic mode” with available equipment.

FIGURE 5. ELECTRIC CHANGES
An electric field applied to complex plasmas causes its properties to change by rearranging its particles, a phenomenon called electrorheology. In the upper panel 6.8-micrometre-diameter particles were used, in the lower panel 14.9-micrometre particles. In both cases the particles aligned along “strings” at the higher field intensities, labelled (b) and (d).

Real Work for Soft Matter?
Are there practical applications for soft matter? Very likely, but instant results should not be expected. German Chancellor Angela Merkel put it best when she said: “People should not expect a basic science discovery made in the morning to deliver an industrial utilisation in the evening.” For instance, it’s generally not well known that about 20% of today’s worldwide economy depends in some manner on quantum mechanics, a theory that first took hold about 100 years ago.

Nevertheless some concrete technological possibilities, derived from complex plasma research, are already being investigated. One is based on fine-particle control in plasma. The concept is to continuously remove dust in plasma etching and plasma vapour-deposition devices where this unavoidable by-product of the manufacturing process causes significant problems, including reduced efficiency. These devices are used for manufacturing items such as flat screens, solar cells, and semiconductor chips.

Other new developments are likely to occur in totally unexpected areas—for instance, in “plasma medicine,” an emerging topic of considerable worldwide interest. The idea is to use room-temperature plasma in a “touch-free” process to treat bacterial and fungal skin diseases. The plasma penetrates the smallest pores and openings, but all the patient feels is a “soothing, warm wind.” There are numerous additional possibilities being discussed, including its use on chronic wounds, in dentistry, surgery and catheters. Even some cancer treatments may be feasible.

The detection of a new state of matter—complex plasma and plasma’s soft matter state—will permit new experimental approaches to the investigation of some major unsolved physics issues. These include an understanding of the organisation of matter at the individual particle level during phase transitions; obtaining a full theoretical kinetic picture of the origin of turbulence; comprehending the scaling phenomena at the transition point between gases and fluids at the kinetic level in phase space; and developing a comprehensive awareness of the fundamental stability principles of condensed matter.

For scientists, any major discovery is always an exciting opportunity, and this one is no exception. It opens up new areas of investigation, creates opportunities for a better understanding of nature’s puzzles, and may ultimately lead to new knowledge and applications that will benefit humanity. The fact that a science lab on the ISS played a critical role in revealing the plasma status of soft matter cannot be overlooked. The examples presented illustrate what can happen when experienced, well-trained experimenters working in weightless conditions are able to carry out unplanned, follow-up research.
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Astronomy
Animal and plant life have been intertwined for hundreds of millions of years. Plants have oxygenated the atmosphere, and the fact that our planet can sustain such a large number of people today is almost entirely due to genetic mutations in wild wheat that occurred at the end of the last Ice Age.

Charles Darwin not only alerted the world to the origin of species, he investigated and described the behaviour of plants in response to their environment, an environment that includes gravity. A strange and interesting form of life, plants pose a conundrum: in the presence of gravity their roots grow downward and away from sunlight, while their stems and shoots grow upward and toward sunlight. How, then, do plants sense gravity? At a very basic level, every plant must have a mechanism that responds to gravitational force by transforming physical stimulus into a biological process.

The study of these effects on living organisms is called gravitational biology. Not a new area of research, numerous investigations have produced a variety of results—some expected, some unexpected, but always fascinating. A historical review of these data reveals different pieces of the larger puzzle—the remarkable adaptability of plants to a condition never encountered in evolution: the near-weightlessness of microgravity.

Roots grow downward while stems shoot upward. Clearly, plants “sense” gravity, but how? Years of research in gravitational biology have yielded some remarkable new insights—and striking contradictions.

By Dieter Volkmann, Anders Johnsson and František Baluška

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AT A GLANCE

- Darwin hypothesized that plant motion is based on both internal processes and external forces such as gravity.
- Research shows that plants grown in near-weightless conditions are more sensitive to gravity than those grown under Earth's gravity.
- Plants will grow in microgravity, but they show disturbances in cell division, photosynthesis and storage reserves.
- Only when multiple generations are grown in space will we get a clearer picture of plant response to microgravity.

—The Editors
Seeds of Research

Our story begins more than 25 years ago. When we began our research, access to the real environment of microgravity in space was limited. So our research began in laboratories with equipment that simulates the absence of gravity: clinostats and centrifuges, random positioning machines and magnetic levitation. Later we were able to use sounding rockets, providing up to six minutes of microgravity. In addition, we also set out to study the other side of the equation—hypergravity, or forces of gravity greater than those experienced on Earth.

By 1983 we were able to get out of the labs and into space. For experiments in microgravity, we used cress and lentil plants because both germinate quickly. In cress seedlings cultivated during flight on the centrifuge under Earth's gravitational conditions, the plant roots showed lower sensitivity to gravitational force compared with those cultivated in microgravity chambers. These findings suggested that an organism grown in microgravity conditions adapts its biological processes in such a way that the organism’s sensitivity to gravity is affected.

Further experiments performed by three European research groups demonstrated that roots from cress and lentil plants are in general highly sensitive to gravitational force. Three plant samples were used: one on the ground, one in orbit in a centrifuge that varied its speed (its acceleration force can mimic the effects of gravity) between Earth’s gravity and one thousandth of Earth’s gravity, and the third, also in orbit, under microgravity conditions (see Figure 1).

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FIGURE 1. ROOT SENSITIVITY
Cress roots cultivated on the centrifuge in orbit and stimulated by various levels of gravity including Earth’s (1g) and observed in stimulus free environment for 60 minutes under reduced gravity. Values across the top indicate stimulation time in seconds. Values across the bottom indicate angle of root bending in relation to root axis. Seedlings grown in microgravity show more prominent root bending, indicating a greater sensitivity to gravity than seedlings cultivated under Earth’s gravity.

such astonishingly low levels of gravity have been well established in animals, which suggests that plants and animals, including humans, share some common response mechanisms to gravity.

The responses seen at various levels of gravity may give some hints about another puzzling question—plant memory. A Venus fly trap, for example, will close after consecutive stimulation of just two sensory hairs, but not one. In our research, every two minutes we applied to cress plant roots a stimulus less than or equal to

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Drs. Volkmann and Baluška have been publishing together in the field of plant signalling and behaviour for several years. Their team in Bonn has participated in experiments on ESA’s Spacelab, sounding rockets and parabolic flights.

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After two to three stimuli, the cress plants responded clearly to repeated stimuli.

**Actin’ Similar**

If plants and humans show similar sensitivity to microgravity, there is presumably a reason. One place to look is at the role of the molecule complex actomyosin. The actin family is a diverse and evolutionarily ancient group of proteins, shared by nearly all forms of organic life. Under normal gravitational conditions, actin’s main roles in both the plant and animal kingdoms are that of structural support as a so-called cytoskeleton within the cells and as an intracellular transport system. Actin combines with another protein, myosin, to form the complex actomyosin, whose role is movement. Given that these proteins share the important role of providing intracellular “scaffolding” that responds to gravity, they may also share other common behaviours that evolved and adapted to the same state of Earth’s gravity.

This hypothesis was tested for the first time on sounding rocket flights using roots from cress plants and single cells called rhizoids from the green algae *Chara* that function like a root. A reaction was seen within six minutes of exposure to microgravity in both the rhizoids and in statocytes, specialised cells in the cress root caps that are involved in gravity perception. Within that short time, heavy (with respect to the cell cytoplasm) and sedimentous particles called statoliths, which exist in a web of actin and which settle like a sediment, moved in a direction opposite to the original gravity vector. To isolate gravity as the stimulating force, chemical compounds were added to destroy the actomyosin system. Under these conditions, the statoliths did not move. These results indicate that under normal conditions the position of statoliths is determined by two counteracting forces: an internal force exerted by the actomyosin system and an external gravitational force. Statoliths can reach a stable position in microgravity, but to do so requires a functioning actomyosin system.

Longer and more sophisticated experiments became possible with the advent of 10-day...
Spacelab missions. On one of these missions in 1996, one group used ESA’s Biorack facility to observe the positions of statoliths in lentil root cells when exposed to different gravitational conditions, including the absence of gravity. Again the role of the actomyosin system in statolith positioning was evident (see Figure 2).

**Feel the Rhythm**

While Darwin and his son had emphasised that plant organs move in relation to external influences like gravity and light, they also asserted that plant motion has an endogenous or inner “character.” They called a plant’s rotational, rhythmic movement circumnutation, and it is affected both by gravity and by internal processes. In simple terms, circumnutation can be described as a spiral movement around a central axis such as the plumb line. If you were to observe a quick-growing plant for a block of time, you would see the tip nod successively around the points of a compass (see Figure 3).
Can clear differences in the behaviour of cell groups when exposed to microgravity be explained by the differences in family or species, or are there other forces at work? And if so what?

The reason for this is the unequal growth rates of plant cells on either side of the central axis. Cells on one side of the plant’s axis stretch, while those on the other side do not; then vice versa. These rhythmic and synchronized changes occur as cells periodically change their shape around the plant stem in order to grow upward. To create unified revolutions, plant cells must be in tune with and respond to the movements of their neighbours. The period of circumnutation in plants fluctuates widely, typically between 30 and 120 minutes and amplitudes vary.

Darwin’s hypothesis that these vigorous movements of plant shoots around the plumb line had an inner origin could be questioned since gravity-oriented movements could be the decisive mechanism. In fact, several experiments point to the importance of gravity in rhythmic movement. Some plants stop their circumnutations under weightless conditions simulated by a clinostat; in others, the period of circumnutations changes on a centrifuge; and mutant plants that do not grow according to the pull of gravity (agravitropic plants) have shown less movement.

To test Darwin’s hypothesis, studies on the influence of gravity on plant circumnutation were carried out during the first Spacelab mission in 1983 when an international consortium from the US and Europe used the stems of sunflowers for its investigations. Careful recordings showed that circumnutations did not totally cease in weightlessness. Even if their amplitude diminished drastically, rotations were less frequent and had a shorter duration. It would appear that Darwin’s hypothesis, put forward more than 100 years ago, is basically correct: plants do have an endogenous “character,” but gravity plays a role as well.

Details, Details

More than a century later, what Darwin called “character” is the study of plant biomechanics, a large field concerned with the mechanical principles that govern a living organism, right down to the function of each living cell. In plants, an important area of biomechanical research is the cell wall. Cell wall components, in particular the composite of cellulose and lignin—the latter is exclusively found in land-based plants—have been characterized as the “backbone” of plants living on land. Because these plants evolved in an environment subject to gravity, long-term experiments in microgravity were expected to prove that they need those backbone-like cell wall components to function properly.

Two teams were involved in this investigation, but came to different conclusions. An American group could not find substantial differences in cellulose microfibril (very fine fibre-like strand) organization, cell wall thickening and lignin composition in wheat seedlings after 10 days of spaceflight compared to ground controls. As a result all plants were essentially identical in size, height and cell wall thickness, regardless of the gravitational field they experienced.

However, a Japanese group obtained different results under similar microgravity conditions. They saw increased elongation accompanied by increased mechanical extensibility of cell walls and decreased cellulose volume for different plant species and organs. While cell wall composition and the underlying metabolism do vary according to plant families, sometimes even to the species level, the question remains: can clear differences in the behaviour of cell groups when exposed to microgravity be explained by the differences in family or species, or are there other forces at work? And if so what?

Space-grown plants also showed a reduction in certain photosynthetic activities. Under light-saturated photosynthetic conditions, the transport rate of electrons was reduced by 28%. This transport process begins when chlorophyll reacts to light and loses an electron, which is then passed through a chain of individual reactions as a key source of energy. There were also changes reported in chlorophyll content, structure and number of chloroplasts within plant cells, and a decrease in the number and size of starch grains in the chloroplasts. These results have been supported by other experiments. No differences, however, were found in photosynthetic activity at the moderate light levels.

Again, results from these early experiments were fraught with contradictions. The most recent space experiments were conducted using
more advanced equipment with careful controls, and no remarkable differences in plant morphology and cell structures have been reported. In reviewing this research, one of the things we have learned is the importance of controlling for changes in the gas exchange process. In microgravity, convection—physically driven heat transfer—is prevented. When that movement is reduced, exchange of gases such as oxygen, carbon dioxide and ethylene is incomplete and has to be supported by sophisticated equipment. During early phases of development, seedlings—particularly their roots—consume oxygen. In the later stages, the concentration of carbon dioxide as well as ethylene dominates plant growth and development. Thus, sophisticated gas control systems are critical to separate the effects of microgravity, heat transfer and even radiation. Early experiments in microgravity did not provide adequate control for gas exchange and created a stress situation for the samples. This might be one explanation for the divergent and sometimes contradictory results.

Sex in Space
It is important to note that not only is microgravity an extremely new area of plant research, but this research is limited by the time available in space to carry out the work. Simply put, plants take time to grow. Sounding rockets provide only 12 minutes at most; ESA’s Spacelab offered around 10 days. To really move forward in this field, we need to observe what happens when plants reproduce in microgravity. Only when a new generation of seeds can be grown in microgravity will any long-term developmental effects between seedlings be observed.

So far most reproductive plant experiments have been performed on the Russian space station Mir and more recently on the International Space Station. One study showed that cell and organ polarity of young seedlings and mature plants cultivated in microgravity did not deviate significantly from control groups. Several corresponding reports agree that gravity is not required for germination, proper growth or development of seedlings, plants and even embryos of the second generation.

Nevertheless, the quality of seeds from generations grown in microgravity is different. Arabidopsis thaliana, a small flowering plant widely used as a model organism in plant biology, has been cultivated on Mir. Seeds from these plants had 20% less storage tissue than found in seeds harvested from ground controls. Examination of the cell chemistry of storage reserves showed that starch was retained in the spaceflight group, whereas protein and lipids were the primary storage reserves in ground control seeds. Protein bodies of plants produced in space were 44% smaller than those in the ground control seeds. Developmental markers indicate that seeds and pollen produced in microgravity were physiologically younger than those produced under Earth’s gravity. From those results, researchers hypothesized that microgravity limits gas mixing even inside tissues and that the resulting gas composition surrounding the seeds and pollen retards their development.

Other researchers in the US and Europe have observed differences in developmental processes at the cellular level between in-flight specimens and controls (see Figure 4). These differences were not only related to storage of materials such as starch, lipids and proteins but to cell division when anomalies were seen in chromosomes, cytoskeletal elements and cell wall components. In particular, one report illustrated the negative effects of microgravity on the cell division cycle. The initial phase of this process was prolonged; and then, when the chromosomes began to divide, breakage and fracture occurred. This suggests that microgravity might exert stress on fast-developing seedlings as well as on cell cultures. Although plants can adapt to this environment, coping with multiple

**FIGURE 4. ROOT GROWTH**
Cress roots in ground controls (above), and under reduced gravity (below). Roots in the control group grow straight down while those in the experimental group bend at various angles.
effects from reduced gravitational force, decreased convection as well as radiation are probably responsible for these outcomes.

**Gene Machines**

Given the complexity of a living organism’s response to gravity, genetics must play a part in those regulatory processes. Experiments have been performed in ground-based laboratories using microscopic array analysis with *Arabidopsis thaliana*. The results showed differences in the expression pattern for up to 200 genes that code for different classes of proteins including transcription factors, cell wall modifying enzymes, cytoskeletal elements and signaling molecules. The relative increase or decrease in several genetic components occurred quickly—within two minutes after changing the plants from a vertical (normal) to a horizontal position (see Figure 5).

Because there are few research opportunities on long term space flights, most of the currently available data were achieved with experiments performed under hypergravity and under simulated weightlessness. Results from two groups using young seedlings and cell cultures of *Arabidopsis thaliana* suggest that changes occur in gene expression under various gravitational conditions and in different classes of genes; and changes in the latter have been seen in plants under other forms of stress. By comparing the expression patterns of selected genes from *Arabidopsis thaliana* seedlings, data showed that genes coding for cell wall modifying enzymes, cytoskeletal elements and signalling molecules are regulated in an opposite manner under hypergravity versus simulated microgravity on a clinostat.

**Adaptation and Exploration**

Viewing these gravity-based experiments retrospectively, we begin to form a more complete picture of the various molecular and cellular effects that range from disturbances in cell division to changes in photosynthetic and reserve storage products. Because these findings often appear contradictory, it is important to interpret them in the context of plant type, culture conditions and experimental procedures.

Nevertheless, a common theme can be teased out from this wealth of data: plants will finally develop under these stressful conditions more or less normally, and they are able to produce seeds over subsequent generations. These results are a testament to the remarkable capacity of plants to adapt to novel stress situations never encountered during the evolutionary process.

This is undoubtedly good news for astronauts on future missions as live, growing plants would be a potential resource for food and oxygen on long journeys into the depths of the solar system. However, there is an even more fundamental aspect to the research. In almost all fields of biology, the deeper you probe as a researcher, the more complicated things appear. So the more you can isolate particular factors, such as gravity, the clearer the picture becomes. It took the discovery of the Rosetta Stone to reveal that Egyptian hieroglyphics were not incomprehensible pictographs, but a complex and sophisticated language.

The “character” of plants is ultimately what we are exploring, and future experiments in space must include research into sensing and signaling of gravity, gravity as a driving factor of evolution and plant adaptation to various stress situations. Obviously if plants are to become important in human exploration of the solar system, then we need to know much more about the production of multiple generations, the maintenance of seed quality and mass production, especially if we want to use them for food and oxygen production. Plants might also contribute to the psychological wellbeing of astronauts traveling vast distances across the solar system. Meanwhile, back on Earth, in a time when food production has suddenly become a major issue, the more we can learn about plants the better—and microgravity research is now a part of that ‘toolbox’.

![Figure 5. Quick Response](image)

Cress root under normal gravity, 24h after activation in standard vertical position (left), followed by 2h stimulation in horizontal position (right). The root quickly responds to a change in the gravity vector.
Meteorites: Stones with Stowaways?
By Frances Westall and Rosa de la Torre Noetzel


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The Puzzle of Plants
By Dieter Volkman, Anders Johnsson and František Baluška


ESSENTIAL TOOLS

Sounding rockets play a crucial role in European microgravity research. The rockets provide up to 13 minutes of high quality microgravity levels at a relative low cost. The short turnaround time and flexible working procedures make it possible for the scientist to include the latest ideas in their experiments. The experiments performed on sounding rockets have produced high quality scientific results in many disciplines.

Swedish Space Corporation has been a provider of complete sounding rocket systems since 1987.

A scientist works on samples about to be launched as part of a microgravity science payload. The Esrange Space Center in Kiruna, Sweden, provides comprehensive facilities for scientific researchers.

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