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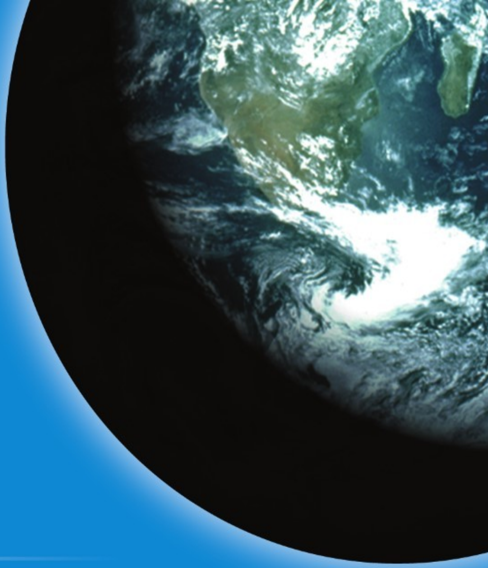

Gilles Clément

Fundamentals of Space Medicine

Second Edition

Space Technology Library

Springer

FUNDAMENTALS OF SPACE MEDICINE

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Second Edition

by

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Foreword

In the summer of 1993, I was fortunate enough to be a student in the International Space University summer session program (SSP), which convened in my then hometown of Huntsville, AL. I was one of the two lucky selectees to represent the NASA Marshall Space Flight Center at SSP'93. ISU has since changed the name of the SSP to Space Studies Program. This happened several years back when we realized that when an SSP convened in the southern hemisphere, such as Chile in 2000, it did not occur during "summer." But that's another story.

The story of 1993 is that attending SSP changed my life – at many levels, all good. Because that summer, this French gentleman approached me during the SSP tour of the Jack Daniel's Distillery up in Lynchburg, TN. In case you're not familiar with the nuances of alcohol regulation in the southeastern United States, Lynchburg is in a "dry" county, so we were not able to sample the product! So the French gentleman and I had a very enjoyable, memorable, and sober conversation. He later turned up to deliver life sciences lectures in the SSP, which were all just great! Little did we know where things would go from there.

Fast-forward to 2004 and the SSP session in Adelaide, Australia. I think the name change happened at about that time. Over the years, I had also become quite entangled with the ISU, returning to the SSP in 1994 in Barcelona as a team project "expert," joining the ISU faculty in 1998, and teaching at SSP sessions nearly annually since then. Now, here I am in Strasbourg as the ISU Associate Dean and SSP Director! At every SSP session I attended, Gilles Clément was always there, doing an absolutely marvelous job of directing the Space Life Sciences Department and giving lectures that absolutely blew everyone away. His creativity and use of animation, video clips, and sound were inspirational to me. I've incorporated many of his "tricks" and showmanship into my somewhat less than entertaining lectures on satellite subsystems design and other such technical topics.

He and I developed a close professional relationship over the years. It was always a joy to arrive at an SSP and see Gilles, along with our many other colleagues and associates. The best memories of those times are of when we would all be together talking, having a few beers, or just hanging out. In 2004, due primarily to cost constraints, many of the usual suspects with whom Gilles and I usually hung out during SSPs were not able to come. So basically, it was just us. We were of course obliged to uphold the traditional night out for beers, banter, and catching up, so we located the Belgian Beer Café in Adelaide and made it our place of retreat. One thing led to another, and well, here we are. I've been his trusty sidekick and editor ever since.

Gilles Clément not only brings an enormous talent to the classroom. He has marshaled his inquisitive nature and remarkable cleverness to orchestrate what must be one of the most impressive research careers in space life sciences ever. He has and continues to perform research on astronauts and cosmonauts, something he's been doing for nearly 30 years now. He has flown experiments on *Salyut*, *Mir*, the space shuttle, and the International Space Station, testing over 100 humans flying in space. His ingenuity and insight have led to a plethora of discoveries and enormously enriched the body of knowledge regarding how microgravity and the space environment affect the human vestibular system. Gilles knows how to translate and transfer research work done in ground-based laboratories into reliable flyable space-based experiments with maximum information return on investment using elegant and simple experimental designs. I have been and continue to be profoundly impressed with how easy it is for him to develop an idea, turn that idea into a scientific hypothesis, and then develop an experimental method and the hardware to effectively and efficiently collect the data needed to resolve the question. Which raises more questions, leading to even more brilliant ideas and experiments. He knows how to do it better than anyone else I have ever worked with.

For me, editing this book was a joy. It gave me the opportunity to dust off my bioengineering degree and to refresh things I knew while learning a whole lot of new things that I didn't. I've enjoyed editing the other three books he has published since 2004, including *Artificial Gravity*, to which I could actually contribute content! It is a wonderful thing that Gilles has now composed four amazing books, sharing his experience and knowledge in a way that is accessible and enjoyable. I appreciate that he's taken the time to revise this one – I know that many students and professionals alike will benefit from this publication and hopefully be inspired by what they find between the covers. I know I am.

15 November 2010

Angie Bukley, Ph.D.
Aerospace Engineer
ISU Associate Dean & SSP Director
Strasbourg, France

Preface

I wrote the first edition of *Fundamentals of Space Medicine* in 2003, when the *Columbia* tragedy grounded the space shuttle for nearly 3 years. My friend Doug Hamilton, a flight surgeon at the NASA Johnson Space Center who knew personally some of the *Columbia* crewmembers, had written a touching preface, dedicating this book to the memory of space travelers who give their lives for the advancement of space life sciences in general and space medicine in particular.

Today, I am writing the second edition of *Fundamentals of Space Medicine* just as the space shuttle will soon complete its last two space missions. By the middle of 2011, the shuttle fleet will be grounded forever, and a page in the history of space exploration will be turned. For the foreseeable future, the only vehicles allowing access of humans to space will be the Russian *Soyuz* and the Chinese *Shenzhou*. Russian, European, and Japanese automatic cargo vehicles will also dock with the International Space Station (ISS) to bring resources for the crew, equipment, fuel, and to return trash.

Fortunately, new spacecraft are in development, boosted by the commercial space and space tourism opportunities. The *Orion* and other new space vehicles developed by commercial companies for the National Aeronautics & Space Administration (NASA) in the United States will hopefully soon provide human access to the ISS. On a different scale, the commercial version of *SpaceShipTwo* is scheduled to fly by next year and will carry loads of paying passengers on suborbital flights up to 100 km in altitude, the official frontier of space. Much needs to be learned on the adaptation of the human body to the first minutes of microgravity, which was never fully investigated on board *Soyuz* and the space shuttle. So the advent of suborbital flight might prove an interesting opportunity for space medicine as well.

The International Space Station is now in its tenth year of existence, with a permanent crew of 6 people and 13 world-class laboratories equipped for state-of-the-art research in life sciences, material sciences, Earth observations, and space science. During the past decade, many experiments and observations were conducted in orbit in the area of space biology, physiology, and medicine, which have complemented the results previously obtained on the *Mir* and *Skylab* missions. The equipment and procedures used in orbit have become more and more accurate and refined, bringing new insights into the mechanisms of body adaptation to the conditions of spaceflight. Ground-based simulations of these effects, as well as studies in analog environments on Earth, have also provided useful models and new research questions. The main results of these experiments are included in this new edition, together with the results of the latest bio-satellite missions and ground-based studies in analog environments on Earth.

Why this title, *Fundamentals of Space Medicine?* Space medicine and space physiology are often viewed as two aspects of space life sciences, with the former being more operational, and the latter being more investigational. Space medicine tries to solve medical problems encountered during space missions. These problems include some adaptive changes to the environment (microgravity, radiation, temperature, and pressure) as well as some non-pathologic changes that become maladaptive on return to Earth (e.g., bone loss). Space physiology tries to characterize bodily responses to space, especially microgravity. It provides the necessary knowledge, hence the "fundamentals," required for an efficient space medicine.

Space physiology and medicine is as old as the first flight of humans in a hot air balloon, when the symptoms of hypoxia were first discovered (at the expense of one pilot's life). The interest in this field of research kept growing along with the space program and the opportunities it provided for more and more humans to fly in space on board capsules, shuttles, space stations, and soon suborbital spaceplanes. The future of human spaceflight will inevitably lead to human missions to Mars. These missions will be of long duration (30+ months) in isolated and somewhat confined habitats, with the crew experiencing several transitions in levels of gravity (1–0 g, 0–0.38 g, 0.38–0 g, and 0–1 g), dangerous radiation, and the challenges of landing and living on their own on another planet.

In *The Fundamentals of Space Medicine* Second Edition, special emphasis has been placed on the challenges, tasks, and research questions that must be addressed before safely sending humans to explore Mars. The greatest test for space medicine will be the projected nearly 3-year round-trip to Mars, whereas our current knowledge on humans in space does now not exceed 14 months and for only one individual, and the cumulative time in space by all astronauts and cosmonauts as of today is comparable to the lifetime of one single individual. The Achilles' heel of the Mars mission may be some adverse reactions of the human body, such as bone loss, decreased motor and sensory capabilities, or simply psychological issues. A chain is as strong as its weakest link. Possible ways to prevent problems and countermeasures are discussed throughout the book.

This book reflects *what we do know* in space life sciences at the beginning of the twenty-first century. It also points to the missing data, i.e., *what we don't know* and *what we should know* before committing to increased access for humans in space, including space commercial participants, by contrast with the professional astronauts, and for longer duration exploratory missions.

The format of the book is intended to facilitate its use by professors, undergraduate or graduate students, space life scientists, and space enthusiasts. It reviews step by step the changes in the major body functions during spaceflight, from the cellular level to the behavioral and cognitive levels. To better appreciate these changes, each chapter starts with a brief review of the basic principles of these human physiological functions on Earth:

- Chapter 1 begins with an introduction to the environmental challenges that spaceflight poses to the human body, and continues with a short history of space life sciences research.
- Chapter 2 reviews the effects of microgravity and radiation at the cellular level on bacteria, animals, plants, and humans, including the issues of reproduction and development.
- The following chapters each review the effects of spaceflight on the major human body functions: Chapter 3: Neuro-sensory function (the brain in space); Chapter 4: Cardio-vascular function (the heart in space); Chapter 5: Musculo-skeletal function

(the muscle and bone in space); Chapter 6: Psychological issues (the mind in space).
- However, every system or process must ultimately be viewed in the context of the entire body. The consequences of the aforementioned changes at a function level on the health and well being of the astronauts are therefore described in the Chapter 7: Operational Space Medicine.
- Chapter 8 focuses on the technical aspects related to life support systems, including radiation shielding, and the challenges for a closed, environmental system for exploration missions.
- Chapter 9 concludes this review with some tips from the author on how to proceed with proposing and planning a space experiment that uses humans as test subjects, given the available resources and constraints of current space missions.

Each chapter corresponds to one core lecture of the Space Life Sciences Department of the International Space University Space Studies Program. These lectures were developed with the help of many people from all over the world in a collegial and collaborative environment. In particular, the sections related to the medical effects of spaceflight are a contribution of my old friend and "partner in crime" at ISU, Doug "Hami" Hamilton. Some of the updates that are included in this revision have been taken nearly verbatim from books that I have published since the first edition of this book came out.

As a neurophysiologist actively participating in space research since 1982, with experiments manifested on *Salyut*, *Mir*, the space shuttle, and the International Space Station, I know what it takes to collect data during relatively simple space experiments, and then try to make sense of the sparse, often contradictory, results in a scientific paper. This book provides a summary of the main results, observations, and trends described in the literature. I apologize to the authors of the scientific publications if all of their interpretations are not included. The detailed descriptions of this research and the findings can be found in the studies listed in the bibliography. A list of other books on space life sciences is also provided.

Some space-related physiological changes and their underlying mechanisms and interpretations are sometimes described in the text in greater detail than what is required for a plenary academic lecture. For the courses I teach at ISU I have prepared PowerPoint presentations corresponding to each of the chapters in this book. These presentations include key concepts in bullet-form illustrated by recent relevant photographs and video clips. PDF versions of these presentations as well as the video clips are included on the website Springer Extras.

The first edition of this book has been translated into Chinese (see front cover in Figure 1). Should there be sufficient demand, no doubt the publisher of this book would be interested in producing other translated versions.

Finally, thanks to Angie Bukley for editing this book and being there for me.

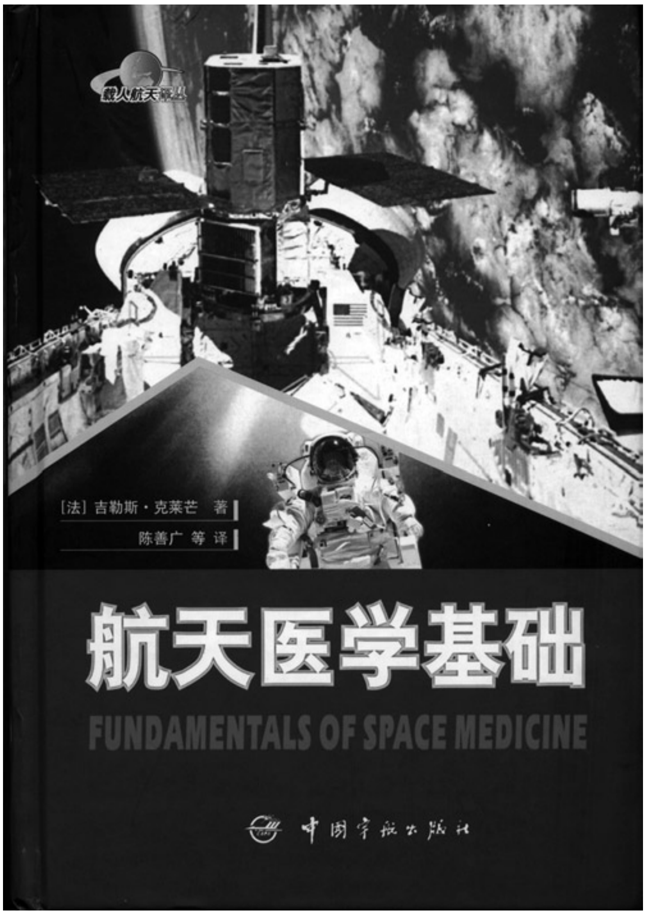

Figure 1 The Front Cover of the Chinese Version of Fundamentals of Space Medicine (First Edition).

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Chapter 1

Introduction to Space Life Sciences

This first chapter describes the hazards that the space environment poses to humans, and how spaceflight affects the human body (where we are). We will then review the historical context of human spaceflight (how we got there), and end with the challenges facing humans in space (where do we go from here) (Figure 1.1).

1.1. Space life sciences: what is it?

1.1.1. Objectives

Life sciences are specifically devoted to the workings of the living world, from bacteria and plants to humans, including their origins, history, characteristics, habits, you name it.

The study of life on Earth ranges from elucidating the evolution of the earliest self-replicating nucleic acids to describing a global ecology comprising over 3 million species, including humans. However, throughout its evolution, organisms on Earth have experienced only a 1-g environment. The influence of this omnipresent force is not well understood, except that there is clearly a biological response to gravity in the structure and functioning of living things. The plant world has evolved gravity sensors; roots grow "down" and shoots grow "up." Animals have gravity sensors in the inner ear. Many fertilized eggs and developing embryos (amphibians, fish, birds, and mammals) also have clear responses to gravity. For example, the amphibian egg orients itself with respect to gravity within a few minutes after fertilization. During that short time the dorso-ventral and anterior-posterior axes of the future embryo are established. Do we conclude therefore that the gravitational input is a required stimulus for the establishment of these axes?

To better understand a system, the scientific method consists of studying the consequences of its exclusion. This approach has led to considerable advances in the knowledge of human physiology, thanks to the nineteenth century physiologist Claude Bernard, who set out the principles of experimental medicine. Clearly, the removal of gravity is a desirable, even necessary, step toward understanding its role in living organisms. In a sense, removal of gravity for studying the gravity-sensing mechanisms is like switching off the light for studying its role in vision. Transition into weightlessness abolishes the stimulus of gravity by a procedure physiologically equivalent to shutting off the light. What can be accomplished in such an elegant fashion aloft can never be done in Earth-based laboratories.

G. Clément, *Fundamentals of Space Medicine*, Space Technology Library 23,
DOI 10.1007/978-1-4419-9905-4_1,

Figure 1.1. The Goal of Space Medicine Is to Develop Methods to Keep Humans Healthy in Space for Extended Periods of Time, as Well as Improve Overall Health of People of All Ages on Earth. (Credit Philippe Tauzin).

Space physiology is of basic scientific interest and deals with fundamental questions concerning the role of gravity in life processes. Space medicine is another, albeit more applied, research component concerned with the health and welfare of the astronauts and space travelers. These two objectives complement one another and constitute the field of space life sciences. In short, space life sciences open a door to understanding ourselves, our evolution, and the workings of our world without the constraining barrier of gravity.

Space life sciences are dedicated to the following three objectives:

Enhance fundamental knowledge in cell biology and human physiology – Access to a space laboratory where gravity is not sensed facilitates research on the cellular and molecular mechanisms involved in sensing forces as low as 10^{-3} g and subsequently transducing this signal to a neural or hormonal signal. A major challenge to our understanding and mastery of these biological responses is to study selected species of higher plants and animals through several generations in absence of gravity. How do individual cells perceive gravity? What is the threshold of perception? How is the response to gravity mediated? Does gravity play a determinant role in the early development and long-term evolution of the living organism? These studies of the early development and subsequent life cycles of representative samples of plants and animals in the absence of gravity are of basic importance to the field of developmental biology.

Protect the health of astronauts – As was amply demonstrated by Pasteur, as well as countless successors, investigations in medicine and agriculture contribute to and benefit from basic research. Understanding the effect of gravity on humans and plants has enormous practical significance for human spaceflight. For example, the process of bone demineralization seen in humans and animals as a progressive phenomenon occurring during spaceflight is not only a serious medical problem. It also raises the question of abnormalities in the development of bones, shells, and the otoliths of the inner ear in species developing in the absence of gravity. The study of such abnormalities should provide insight into the process of biomineralization and the control of gene transcription.

Develop advanced technology and applications for space and ground-based research – In addition to the scientific need to study basic plant and animal interactions with gravity, there is a practical need to study their responses. These are essential to our ultimate ability to sustain humans for a year or more on the surface of extraterrestrial bodies or in spaceflight missions of long duration where re-supply is not possible, and food must be produced in situ. Experiments during long-duration space missions will determine which plants and animals are most efficient and best suited for our needs. For instance, can soybeans germinate, grow normally, produce optimum crops of new soybeans for food and new seed for ensuring future crops? All of this biological cycling, plus the development of equipment for water and atmospheric recycling, plus management of waste, will also bring important benefits for terrestrial applications. Also, the absence of gravity is used to eliminate micro convection in crystal growth, in electrophoresis, and in biochemical reactions. The resulting products can be used for both research and commercial application.

Space life sciences include the sciences of physiology, medicine, and biology, and are linked with the sciences of physics, chemistry, geology, engineering, and astronomy. Space life sciences research not only help us to gain new knowledge of our own human function and our capacity to live and work in space but also to explore fundamental questions about gravity's role in the formation, evolution, maintenance, and aging processes of life on Earth (Table 1.1).

Table 1.1. Major Applications of Space Life Sciences Research.

Biology

- Advance understanding of cell behavior
- Improve crop yields using less nutrients and smaller surface and volume

Biotechnology

- Provide information to design a new class of drugs to target specific proteins and cure specific diseases
- Culture tissue for use in cancer research, surgery, bone cartilage, and nerve injuries

Medicine

- Enhance medical understanding of disease processes such as osteoporosis
- Advance fundamental understanding of the nervous system and develop new methods to prevent and treat various neurological disorders
- Develop methods to keep humans healthy in low-gravity environments for extended time periods

Education

- Use science on orbit to encourage and strengthen science education on Earth

1.1.2. The space environment

The space environment (radiation, microgravity, vacuum, magnetic fields) as well as the local planetary environments (Moon, Mars) have been extensively reviewed in Peter Eckart's book *Spaceflight Life Support and Biospherics* (1996). In this section, we will mainly focus on microgravity. The medical issues related to space radiation will be developed in Chapter 8.

1.1.2.1. Microgravity

The presence of Earth creates a gravitational field that acts to attract objects with a force inversely proportional to the square of the distance between the center of the object and the center of Earth. When we measure the acceleration of an object acted upon only by Earth's gravity at Earth's surface, we commonly refer to it as *1 g* or one Earth's gravity. This acceleration is approximately 9.8 m/s^2.

We can interpret the term *microgravity* in a number of ways, depending upon the context [Rogers et al. 1997]. The prefix micro- derives from the original Greek *mikros,* meaning "small." By this definition, a microgravity environment is one that imparts to an object a net acceleration that is small compared with that produced by Earth at its surface. We can achieve such an environment by using various methods, including Earth-based drop towers, parabolic aircraft flights, and Earth-orbiting laboratories. In practice, such accelerations will range from about 1% of Earth's gravitational acceleration (on board an aircraft in parabolic flight) to better than one part in a million (on board a space station). Earth-based drop towers create microgravity environments with intermediate values of residual acceleration.

Quantitative systems of measurement, such as the metric system, commonly use micro- to mean one part in a million. By this second definition, the acceleration imparted to an object in microgravity will be 10^{-6} of that measured at Earth's surface.

The use of the term *microgravity* in this book corresponds to the first definition: small gravity levels or low gravity.

Microgravity can be created in two ways. Because gravitational pull diminishes with distance, one way to create a microgravity environment is to travel away from Earth. To reach a point where Earth's gravitational pull is reduced to one-millionth of that at the surface, we would have to travel into space a distance of 6.37 million kilometers from Earth (almost 17 times farther away than the Moon). This approach is impractical, except for automated spacecraft.

However, the act of free fall can create a more practical microgravity environment. Although aircraft, drop tower facilities, and small rockets can establish a microgravity environment, all of these laboratories share a common problem. After a few seconds or minutes of low-g, Earth gets in the way and the free-fall stops. To establish microgravity conditions for long periods of time, one must use spacecraft in orbit. They are launched into a trajectory that arcs above Earth at the right speed to keep them falling while maintaining a constant altitude above the surface.

Newton [1687] envisioned a cannon at the top of a very tall mountain extending above Earth's atmosphere so that friction with the air would not be a factor, firing cannonballs parallel to the ground. Newton demonstrated how additional cannonballs would travel farther from the mountain each time if the cannon fired using more black

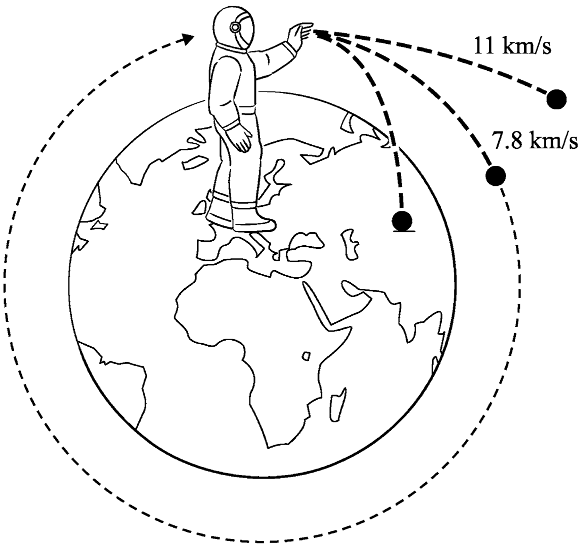

Figure 1.2. Artificial Satellites Are Made to Orbit Earth When Their Velocity Is Equal or Higher Than 7.8 km/s. When in Orbit, the Spacecraft and Its Inhabitants Are in a State of Continuous Free-Fall with No Apparent Perception of Gravity. (Credit Philippe Tauzin).

powder. With each shot, the path would lengthen, and soon the cannonballs would disappear over the horizon. Eventually, if one fired a cannon with enough energy, the cannonball would fall entirely around Earth and come back to its starting point. The cannonball would begin to orbit Earth. Provided no force other than gravity interfered with the cannonball motion, it would continue circling Earth in that orbit (Figure 1.2).

This is how the space shuttle stays in orbit. It launches into a trajectory that arcs above Earth so that the orbiter travels at the right speed to keep it falling while maintaining a constant altitude above the surface. For example, if the space shuttle climbs to a 320-km high orbit, it must travel at a speed of about 27,740 km/h to achieve a stable orbit. At that speed and altitude, due to the extremely low friction of the upper atmosphere, the space shuttle executes a falling path parallel to the curvature of Earth. In other words, the spacecraft generates a centrifugal acceleration that counterbalances Earth's gravitational acceleration at that vehicle's center of mass. The spacecraft is therefore in a state of free-fall around Earth, and its occupants are in a microgravity environment. Gravity *per se* is only reduced by about 10% at the altitude of low Earth orbit (LEO), but the more relevant fact is that gravitational acceleration is essentially canceled out by the centrifugal acceleration of the spacecraft.

1.1.2.2. Other factors of the space environment

Beside microgravity, during spaceflight living organisms are also affected by ionizing radiation, isolation, confinement, and changes in circadian rhythms (the 24-h day-night cycle). In plants, for example, spaceflight offers the unique opportunity to separate the gravitational input from other environmental stimuli known to influence