Michael R. Barratt
Ellen S. Baker
Sam L. Pool
Editors

Principles of Clinical Medicine for Space Flight

Second Edition

Springer

Principles of Clinical Medicine for Space Flight

Michael R. Barratt • Ellen S. Baker • Sam L. Pool
Editors

Principles of Clinical Medicine for Space Flight

Second Edition

Springer

Editors
Michael R. Barratt, MD, MS
NASA Johnson Space Center
Houston, TX
USA

Sam L. Pool, MD
Deceased, Formerly Chief
Medical Sciences Division
NASA Johnson Space Center
Houston, TX
USA

Ellen S. Baker, MD, MPH
Gynecologic Oncology and Reproductive
Medicine, University of Texas, MD Anderson
Cancer Center
Houston, TX
USA

ISBN 978-1-4939-9887-6 ISBN 978-1-4939-9889-0 (eBook)
https://doi.org/10.1007/978-1-4939-9889-0

This Springer imprint is published by the registered company Springer Science+Business Media, LLC part of Springer Nature.
The registered company address is: 233 Spring Street, New York, NY 10013, U.S.A.

Foreword to the First Edition

The space environment does strange things, both to the workings of the human body and to the behavior of ordinary medical equipment. Space medicine describes the "normal person in an abnormal environment" and is an outgrowth of aviation medicine.

Aviation medicine didn't exist when my father was born in 1884. By the time he served in the Army during World War I, it did, but its medical standards were still under construction. The Air Service Medical Manual issued by the War Department in 1918 discussed the public's impression that the medical examination of an aviator was "a form of refined torture." One story was that of the needle test. This mythical examination supposedly involved placing a needle between the candidate's forefinger and thumb, blindfolding him, then shooting off a pistol behind his ear. The examiner would then note whether, owing to a supposed lack of nerve, the applicant had pushed the needle through his finger. The test sounded plausible then.

Aviation medicine as a specialty grew quickly during World War II and the onset of the jet age in the 1950s. However, when the space age dawned suddenly with Sputnik in 1957, medicine was not ready. The pages of the Journal of Aviation Medicine for the years 1959 through 1961 were filled with forecasts of the effects of "zero G" on the human body—most of them dire. For example, doubt was expressed whether the gastrointestinal system would function when weightless; nourishment, it was reasoned, might have to be given intravenously. The altitude and solitude, it was opined, would cause "break off phenomenon," a sort of psychosis of loneliness. My favorite of these predictions was that space travelers weren't going to be able to urinate. This was "proven" in an experiment wherein a rookie medical technician was strapped into the back seat of a jet fighter-trainer, helmeted, masked, and instrumented, flown to 35,000 ft, then pulled up into a zero-G parabola. At the peak of the maneuver, the pilot cried "Go!" and the poor fellow couldn't do it. Catheters were solemnly recommended for astronauts.

It sure was fun knowing so little about the physiology of weightlessness. Skylab was a prototype space station in which three crews spent 1, 2, and 3 months learning how to homestead in space and to care for ourselves up there. A demand that a physician be on each crew was rejected, but a small medical kit was in place, and two members of each crew—most of whom were test pilots—were trained to sew up cuts, extract teeth, and examine and report on their fellow crewmen. Fortunately, the practice was slow; we never had a serious medical problem to treat.

The U.S. Space Shuttle program, and later the joint NASA–Mir and International Space Station programs, have given the physician-authors of this book experience with hundreds of person-trips into space. The dreaded space motion sickness has been conquered, end-of-mission problems with vertigo and fluid loss have been brought under control, and confidence in human capabilities has been engendered. But true long-duration weightlessness is still a frontier. A Mars mission is still a substantial challenge.

Another critical perspective on space medicine is the recognition of its inherently interdisciplinary nature. Weightless humanity exists only in a special world, a "space craft" crafted by engineers, a closed-loop system with a man-made atmosphere and its own rules of up and down. This pulls doctors into the world of engineers and vice versa. We must help each other solve problems that arise not only from weightlessness but also from where we are and what we're in—a vessel where, to get to Mars, we will have to recycle the very air we breathe and the water we consume. Engineering equipment—medical and otherwise—is a challenge when everything floats and nothing settles.

The details are all in this book. The nature of interplanetary space, its effect on our bodies (and minds), the treatments and countermeasures we currently prescribe, and the mysteries that remain, are graphically described and illustrated. If you are a researcher needing a fact or reference, an engineer who wants to know how your design affects its users, or a curious student drawn to medicine or biology but also to the adventure of space flight—fill your mind here, and let your imagination carry you to Mars.

Exploration of the heavens still has a value independent of the commercial and military arguments we use in its defense. The hunger to know and to see is one of our defining characteristics as human beings. The future does not exist. We get to help write its story.

Houston, TX, USA Joseph P. Kerwin, MD

Foreword

The Next Small Step

Seen from space, the envelope of atmosphere around the Earth within which we are able to live and thrive is precariously thin, appearing as a fragile blue crescent smeared around our planet. Nevertheless that narrowband is—at present—the only natural habitat in the observable universe that we know to be capable of supporting human life. Even within that privileged niche, survival has been no mean feat; centuries of exploration were required before we were able to claw our way into its furthest reaches. And it is only in the last hundred years that we have found ourselves able to probe the full extent of our own globe.

In 1918, at the end of World War I, our ability to protect human life and physiology against the extremes of disease, injury, and the environment was sorely limited. There remained many poles of the Earth that had yet to be trodden by any human foot. And yet within the span of a few decades, science, technology, and engineering together took us to those unexplored limits, beyond into the endless skies and out into the blackness of space.

The specialty of aviation medicine was born during the aerial conflict of The Great War; a recognition that the reliability and fallibility of the human in the loop were as important to these fighting systems as the aircraft themselves. And that appreciation of the relationship between human, machine, and environment would become central to our endeavors at the frontiers of discovery as we pushed on into space.

Where people go, medicine must follow; the same exploration that took us across the globe and out toward the stars also drew us within to explore the limits of the human body. In the earliest days of human spaceflight, clinicians and scientists readily predicted the likely effects of gravitational unloading on our muscles and skeletons. But the impacts of microgravity to human physiology were more widespread and profound than anyone had first imagined: alongside sarcopenia and osteopenia, cardiovascular deconditioning, vestibular impairments, immunoparesis, and alterations in hematopoiesis unmasked themselves. This coupled with the environmental challenges of ionizing radiation, hard vacuum, and thermal extremes confirmed the space environment as uniquely hostile. Our first forays in space—though successful—taught us that we could stay but not for long and not without penalty.

For explorers of the physiology and medicine of this newly encountered extreme, the challenge did not end there. Understanding environmental control and life support systems, their modes of failure and how those failures might be mitigated were also central to their role. Nevertheless the specialty matured apace, continuing its own voyage of discovery, meeting the challenges of a unique population deployed in a unique environment, while learning how best to facilitate our future programs of exploration.

It has now been 50 years since humans first set foot upon the Moon. We can look back across a half century of achievement and marvel at just how far we have come in such a short interval of human history. But despite these great strides, aerospace medicine is still in its infancy. It is arguable that the completion of the International Space Station brings to a close the first space age, in which low Earth orbit went from being a location we visited infrequently and briefly to a place in which professional crews now permanently live and work. The second space age will be defined by the ingress of commercial participants and the challenges of true long duration, exploration class missions. As we push out across tens of millions of interplanetary miles and the population of people who fly in space comes to more closely resemble the wider population here on Earth, there will be fresh challenges to meet. And so the exploration continues.

One hundred years on from the events that gave birth to aviation medicine and 50 years after Neil Armstrong's small step, we must consider the shape of the next giant leap. If we are to achieve all we can in sailing this New Ocean, we will have to better understand its effects on the human body, how to maintain health, and how best to mitigate the consequences of injury and disease in this unique environment. This text represents the latest evolution in our understanding of the effects of the space environment on the human body and a fine distillation of knowledge, acquired from around the globe and across decades of experience. The joy we feel in the pursuit of the discipline of space medicine lies in just how much remains unknown: it continues to be a voyage of exploration and a reminder that the frontiers of medicine are as boundless as those of space itself.

Kevin Fong, MD
Centre for Altitude, Space and Extreme Environment Medicine
University College London
London, UK

Preface to the First Edition

There is no land uninhabitable, nor sea innavigable.

—(Robert Thorne, 1527)

In 1768, Captain James Cook was preparing his vessel, the Whitby collier *Endeavour*, and her crew for an extended sea voyage. At that time, mortality rates of 50% or more were not uncommon for trade voyages. Scurvy, resulting from lack of dietary ascorbic acid (vitamin C), was the great enemy. Cook developed and, with the help of ship's surgeon William Munkhouse, administered to his crew a preventive regimen that included required consumption of "antiscorbutics"—food supplements consisting of such items as onions, sauerkraut, fruit, and occasionally native grasses found on islands en route. Not a single life was lost from scurvy. Subsequent voyages by Cook and countless others were spared from the curse of scurvy, and many lives were thus saved. A new expectation arose: that crews could safely remain at sea for the prolonged periods required to make their voyages.

We now stand near where Cook stood more than 200 years ago. Many bold steps have been taken into space over the past four decades, and we now contemplate still more ambitious missions of exploration and science. The mortality and morbidity rates associated with these preliminary efforts have been relatively low, though certainly not negligible. In taking these early steps, we have gained invaluable knowledge of how humans live in the space environment, particularly with regard to weightlessness. Key adverse influences and effects have been identified, including radiation exposure and acquired dose, bone and muscle atrophy, and cardiovascular deconditioning. Thus far these effects have been tolerable during the course of low-Earth orbit and preliminary lunar explorations. However, future missions will involve greater distances and times and will demand that these effects be countered and other capabilities provided to sustain the human presence and to support optimal work. Our current charge is to expand human exploration while maintaining the safety and health of the exploring crewmembers.

As *Endeavour's* surgeon Munkhouse did, we too have a standard of medical care and safety that must be "taken to sea" with us. To the extent possible and practical, current standards of medicine are expected to accompany space crews on their missions. Along with these standards, a more complete understanding of how the space environment affects the human body is required. The application of standard medical practice in this unique and challenging context defines space medicine as a distinct discipline. In 1968, after the first few years of human space flight, Dr. Douglas Busby wrote *Space Clinical Medicine,* a well-referenced and highly prospective and insightful work. Since that time, a tremendous amount of information has accrued regarding the physiologic effects of weightlessness as well as medical and environmental events occurring during flight that influence crew health. In many ways, this text is a successor to Dr. Busby's fine work. *Principles of Clinical Medicine for Space Flight* was written *by* practitioners of space medicine *for* practitioners of space medicine and for others who may benefit from this knowledge in their own unique circumstances. Neither an overall basic medical text nor a comprehensive review of space physiology, this book focuses on aspects of medicine that arise uniquely and are dealt with uniquely in human space flight, and how the effects of space flight—whether adverse or simply anomalous—are addressed to provide the best care for space crewmembers.

Principles of Clinical Medicine for Space Flight draws heavily on the experience of the U.S. Skylab and Space Shuttle programs as well as the Russian experience with long-duration missions aboard the *Salyut* and *Mir* space stations and, most recently, from our joint work on the first several missions aboard the International Space Station (ISS). Contributors have a rich and practical experience base of direct space mission support and human life sciences research, and this is reflected in the detailed information presented. Readers will find background information on the relevant physical forces and mechanical aspects of spaceflight necessary for complete understanding of the environment and its influence on the human space traveler. This is followed by a comprehensive review of the human response to every aspect of spaceflight, the most likely medical problems encountered, their diagnosis, management, and prevention. Special emphasis is given to those areas most limiting to long duration flights, such as radiation, bone and muscle loss, cardiovascular and neurovestibular deconditioning, nutrition and metabolism, and psychological reactions. Flight crew medical selection and retention standards are addressed, with discussion on rationale and application. In addition, cutting-edge technical issues particularly associated with provision of medical care in space are discussed, including selection and use of medical systems, telemedicine, medical imaging, surgical care, and medical transport. When warranted, reasonable speculations are offered regarding principles of medical support and practice for future exploration missions involving a return to the Moon and interplanetary flight.

There is an expanding niche of medical practitioners who may utilize this book as a standard of care for supporting human space missions. This cadre is international, both civil and military, and is now extending into the commercial sector. This knowledge base should also greatly benefit the many groups and academic institutions involved in space life sciences or other environmental human research. Those participating in aerospace program and mission support and planning which involves or overlaps with medical decision making should also find useful information in this book. In addition, those involved with similar responsibilities of medical support in environments which are analogous to spaceflight, including submarine and surface ships, polar research stations, and other extreme or remote settings may benefit from our findings, as we have often benefited from such venues and exchange of experience. Finally, for the medically curious, we offer a comprehensive reference on one of the very latest medical specialties; none is more fascinating.

The size and scope of this book attests to the technical support and logistical efforts that were required to bring it into being. Our thanks go to technical editors Sharon Hecht and Luanne Jorevich and graphics wizards Sid Jones and Terry Johnson, who went extra miles during extra hours translating space medical jargon into plain English and clear figures; to space life sciences librarians Janine Bolton and Kim So for helping us to mine the world's literature on space medicine; and to Brooke Heathman and Ellen Prejean, who helped organize and mold the chapters into a coherent work. Special thanks go to Chris Wogan, world expert on space life sciences technical literature, for bringing her talents to bear on this project, and to Merry Post and her exemplary skill and patience for guiding the transformation of our knowledge base into a user-friendly text.

Of course our deepest gratitude goes to our families, and especially to our spouses Michelle R. Barratt and Jane Pool, who have weathered our fascinations and obsession with space flight these many long years; we can never adequately repay you for your dedication and support.

Finally, to all of the world's space travelers of all flags and professions who have undergone examination, monitoring, and sampling for medical certification and science for over four decades, we offer heartfelt thanks. A rising space-faring civilization owes you a debt of gratitude for your patience, endurance, and your great contribution to human space flight.

Houston, TX, USA

Michael R. Barratt, MD, MS
Sam L. Pool, MD

Preface

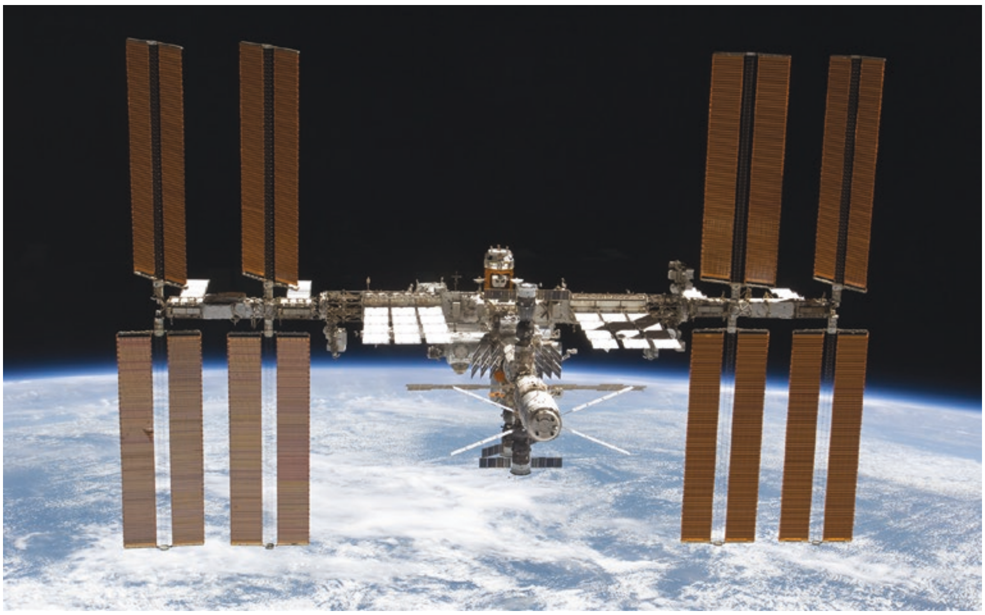
The first decade of human space flight was significant in providing breakthrough understanding of the human response to forces, such as launch and entry accelerations, weightlessness, and environmental stresses. Along with sorties to low Earth orbit and the surface of the Moon, adaptive phenomena were being newly discovered at a rapid pace in keeping with the tempo of the US and Russian programs of the time. Arguably the last 10 years have been equally informative on many levels. In 2009, the year after the first edition of this text was released, the crew of the International Space Station (ISS) was increased to its full complement of six, and the platform's focus shifted from construction to operation of the magnificent and fully functioning laboratory it is today. In this most recent decade, studies aboard the ISS have afforded deeper mechanistic understanding of observed adaptive phenomena, discovery of new and significant additional phenomena, and development of highly effective countermeasures to bone and muscle atrophy of weightlessness. The expectation of healthy, well-adapted crewmembers operating a highly productive science laboratory for standard 6-month missions has been firmly cemented.

In addition, vehicle enterprises have changed. The US Space Shuttle program ended gracefully with the flight of STS-135 in 2011, leaving a rich legacy of hundreds of human spaceflight experiences. The Russian Soyuz has continued to prove itself as the most reliable human carrier in history, delivering crews to and from the ISS in a near clockwork fashion. China has successfully flown the Tiangong-1 and Tiangong-2 orbiting laboratories with short-term crews delivered by the Shenzhou spacecraft, a stepping stone toward a future permanent orbiting station. At the current time, multiple new human-carrying vehicles are in late-stage development, with human design requirements greatly informed by the knowledge base accrued in space medicine and human factors.

Against this backdrop, we are pleased to bring the second edition of *Principles of Clinical Medicine for Space Flight* to the space medical community. It has been a most eventful decade in the human spaceflight world, and many findings demand consolidation into a coordinated work building toward a common understanding and standard of care for those that leave the planet. Material has been updated with the same attention to references and peer review, and the use of figures expanded considerably. Four new chapters have been added, covering medical aspects of extravehicular activity, countermeasures and rehabilitation, pharmacology, and mishap investigation.

Dr. Ellen S. Baker, veteran NASA flight surgeon and astronaut, was brought on as co-editor of this edition to provide another spaceflight-savvy set of eyes to the writings. We have been careful to apply our flight experience in a thoughtful way, recognizing that individual experiences are unique and that holistic understanding requires well-controlled science and methodical review of operational data. Sadly we said goodbye to Dr. Sam L. Pool, co-editor of the first edition and one who had a major hand in shaping operational space medicine at NASA. We have noted him as a senior editor in his memory.

In producing this second edition, we have once again asked some of the world's busiest people to write along their fields of expertise while engaged in full-time research or operational support. We cannot thank them enough for their contributions. We also offer gratitude to our many peer reviewers; this effort is demanding and largely thankless, but vital to sound medical literature. Thanks are also due to our very lean but dedicated administrative support staff. To Brooke Heathman, who tracked and organized hundreds of drafts, figures, permission letters, and other communications, we would not be here without you. To Kim So and Marta Giles, curators of the Johnson Space Center Medical Library, heartfelt gratitude for the hundreds if not thousands of papers pulled for the creation of these chapters. To the staff of the Lifetime Surveillance of Astronaut Health program, notably Adriana Babiak-Vazquez, Mary Van Baalen, and Mary Wear, thanks for making sense of a large and complex data base from which valid answers emerge only with careful extraction. Finally, we salute all of the subject participants in space medical investigations, past, present, and future, whether in space or ground analog studies. You are the backbone of the knowledge base that forms our standard of care.



The International Space Station, viewed from the Space Shuttle Discovery, March 7, 2011

Houston, TX, USA

Michael R. Barratt, MD, MS
Ellen S. Baker, MD, MPH

Contents

Contributors

Christopher S. Allen, BS, MS NASA Johnson Space Center, Houston, TX, USA

Cheryl W. Armstrong, BS International Space Station Program, NASA Johnson Space Center, Houston, TX, USA

Serena M. Auñón, MD, MPH NASA Johnson Space Center, Houston, TX, USA

Kira Bacal, MD, PhD, MPH, FACAsM Faculty of Medical and Health Sciences, University of Auckland, Auckland, New Zealand

Ellen S. Baker, MD, MPH Gynecologic Oncology and Reproductive Medicine, University of Texas, MD Anderson Cancer Center, Houston, TX, USA

Robert Banks, BEng, MD Biodynamic Research Corporation, San Antonio, TX, USA

Michael R. Barratt, MD, MS NASA Johnson Space Center, Houston, TX, USA

George Beck, BA, RRT, FAARC Department of Ventilation Science, ZOLL Medical Corporation, Chelmsford, MA, USA

Gary E. Beven, MD Space Medicine Operations Division, Johnson Space Center, Houston, TX, USA

Roger D. Billica, MD Trilife Health, PC, Fort Collins, CO, USA

Jacob J. Bloomberg, PhD Neuroscience Laboratory, NASA Johnson Space Center, Houston, TX, USA

Mark R. Campbell, MD Paris Regional Medical Center, Paris, TX, USA

Jonathan B. Clark, MD, MPH Department of Neurology, Space Medicine, Baylor College of Medicine, Houston, TX, USA

Tim Cook, MD, FRCPC, MPH, LCol (Retired) Canadian Forces Medical Service, Aviation Medicine Defence Research and Development Canada, Downsview, ON, Canada

Octav Cristea, MD Emory Transplant Center, Emory University School of Medicine, Atlanta, GA, USA

Brian E. Crucian, PhD Biomedical Research and Environmental Sciences Division, NASA Johnson Space Center, Houston, TX, USA

Richard W. Danielson, PhD KBR-Johnson Space Center, Houston, TX, USA

Department of Otolaryngology, Center for Space Medicine, Baylor College of Medicine, Houston, TX, USA

Joseph Dervay, MD, MPH, MMS, FACEP Space Medicine Operations, NASA Johnson Space Center, Houston, TX, USA

Christopher F. Flynn, MD The Office of Aerospace Medicine, Federal Aviation Administration, Washington, DC, USA

C. Robert Gibson, OD Coastal Eye Associates and KBR, NASA Johnson Space Center, Houston, TX, USA

Stevan Gilmore, MD, MPH Department of Human Health and Performance, NASA, Houston, TX, USA

Gary W. Gray, MD, PhD Canadian Space Agency, Toronto, ON, Canada

Mark E. Guilliams, ME, MA KBR, Houston, TX, USA

Douglas R. Hamilton, MD, PhD, MSc KBR to University of Calgary, Houston, TX, USA

Richard Harding, BSc, MB, BS, PhD Biodynamic Research Corporation, San Antonio, TX, USA

Deborah L. Harm, PhD Neuroscience Lab, NASA Johnson Space Center, Houston, TX, USA

Michael H. Hodapp, DDS Private Practice, Houston, TX, USA

John T. James, PhD Department of Environmental Sciences, NASA Johnson Space Center (retired), Houston, TX, USA

Richard T. Jennings, MD, MS Aerospace Medicine Program, Preventive Medicine and Community Health, UT Medical Branch at Galveston, Galveston, TX, USA

Arthur H. Jeske, DMD, PhD Strategic Planning and Continuing Dental Education, UT Health Science Center at Houston, Houston, TX, USA

Smith L. Johnston III, MD, MS NASA Johnson Space Center, Houston, TX, USA

Jeffrey A. Jones, MD, FACS, FACPM, FAsMA Scott Department of Urology, Center for Space Medicine, Baylor College of Medicine/Michael E. DeBakey VA Medical Center, Houston, TX, USA

Fathi Karouia, PhD NASA Ames Research Center, Moffett Field, CA, USA

Eric L. Kerstman, MD, MPH Space Medicine, University of Texas Medical Branch/KBR, Houston, TX, USA

Helen W. Lane, PhD, RD NASA Johnson Space Center, Houston, TX, USA

Jennifer Law, MD, MPH Department of Preventive Medicine and Community Health, University of Texas Medical Branch, Galveston, TX, USA

Stuart M. C. Lee, PhD, MS, BS Cardiovascular and Vision Laboratory, Biomedical and Environmental Research, KBR, Houston, TX, USA

José G. Limardo, PhD NASA Johnson Space Center, Houston, TX, USA

Kjell N. Lindgren, MD, MS, MHI, MPH NASA Johnson Space Center, Houston, TX, USA

Thomas H. Mader, MD Colonel (R), US Army, Moab, UT, USA

F. Keith Manuel, OD Department of Ophthalmology, Baylor College of Medicine, Houston, TX, USA

Thomas H. Marshburn, MD, MSEngr, MS NASA Johnson Space Center, Houston, TX, USA

Shannon Melton, BS KBR, Houston, TX, USA

Shannan Moynihan, MD, MPH Space and Occupational Medicine, NASA Johnson Space Center, Houston, TX, USA

Amy Mumbower, MD Department of Radiology, Biodynamic Research Corporation, San Antonio, TX, USA

Hernando J. Ortega Jr., MD, MPH Aerospace Medicine Division, Headquarters, Air Education and Training Command, United States Air Force, JBSA Randolph, TX, USA

James M. Pattarini, MD, MPH Space Medicine Operations Division, NASA Johnson Space Center, Houston, TX, USA

Duane L. Pierson, PhD Biomedical Research and Operations, NASA, Houston, TX, USA

Robert A. Pietrzyk, MS International Space Station Medical Projects (ISSMP), KBR, Houston, TX, USA

Andrew A. Pilmanis, AB, MS, PhD US Air Force Research Laboratory (retired), Brooks City Base, San Antonio, TX, USA

Lawrence Pinsky, PhD, LLM, JD Department of Physics, University of Houston, Houston, TX, USA

Lakshmi Putcha (Deceased), PhD Pharmacotherapeutics Laboratory, NASA Johnson Space Center, Houston, TX, USA

Millard F. Reschke, PhD Department of Neuroscience, NASA Johnson Space Center, Houston, TX, USA

Valerie E. Ryder, PhD, DABT Department of Toxicology and Environmental Chemistry, NASA Johnson Space Center, Houston, TX, USA

Joan Saary, MD, PhD, FRCPC Division of Occupational Medicine, Department of Medicine, University of Toronto, Toronto, ON, Canada

Canadian Forces Environmental Medicine Establishment, Toronto, ON, Canada

Clarence F. Sams, PhD Space Medicine Operations Division, NASA Johnson Space Center, Houston, TX, USA

Robert W. Sanders, MD, FACEP NBL Medical, Crew Health and Safety Flight Surgeon, UTMB/KBR/NASA-JSC, Houston, TX, USA

Ashot E. Sargsyan, MD Space and Medical Operations, KBR, Houston, TX, USA

Richard A. Scheuring, DO, MS Space Medicine, NASA Johnson Space Center, Houston, TX, USA

Houston Methodist Hospital, Houston, TX, USA

Linda C. Shackelford, MD NASA Johnson Space Center, Houston, TX, USA

Houston Methodist Hospital, Houston, TX, USA

Scott C. Simmons, MS Medweb, LLC, San Francisco, CA, USA

Walter E. Sipes, PhD Aerospace Psychology Consultants, Tucson, AZ, USA

Kieran T. Smart, MBChB, MSc, MPH Department of Primary Care, Bay Pines VA Healthcare System, Bay Pines, FL, USA

Byron A. Smith, BS KBR, Houston, TX, USA

Scott M. Smith, PhD Biomedical Research and Environmental Sciences Division, NASA Johnson Space Center, Houston, TX, USA

Tracy Jo Snow, DO, BS Department of Family Medicine, Hawai‘i Pacific Health Kaua‘i Medical Clinic in Koloa, Koloa, HI, USA

Astronaut Training, NASA, Houston, TX, USA

Terrance A. Taddeo, MD NASA Johnson Space Center, Houston, TX, USA

Moriah S. Thompson, MD, MPH Department of Preventive Medicine & Community Health, The University of Texas Medical Branch, Galveston, TX, USA

Mary L. Wear, PhD Epidemiology Discipline Lead, KBR, Houston, TX, USA

Alexandra Whitmire, PhD Behavioral Health and Performance, KBR/Johnson Space Center, Houston, TX, USA

Peggy A. Whitson, PhD NASA Johnson Space Center, Houston, TX, USA

Virginia Wotring, PhD International Space University, Strasbourg, Alsace, France

Sara R. Zwart, PhD Preventive Medicine and Community Health Division, University of Texas Medical Branch at Galveston, Galveston, TX, USA

Part I

Unique Attributes of Space Medicine

1 Physical and Bioenvironmental Aspects of Human Space Flight

Michael R. Barratt

Life on Earth has developed and flourished under a wide range of diverse circumstances. These include familiar conditions at Earth's surface and in upper layers of the seas, as well as the more exotic subterranean and deep ocean aphotic zones, where oxidative and anaerobic life processes can flourish at extreme limits of temperature, pressure, and exposure to what are classically considered toxic substances. A constant acceleration of 32 ft/s^2 (9.81 m/s^2) that provides the familiar gravitational force, a protective and physiologically supportive atmospheric gas layer, and radioprotective geomagnetic fields comprise the major factors that have profoundly influenced Earth as a place of human life. We are designed to function optimally in this environment—and within a fairly narrow envelope at that. Without protective methods and devices, human beings are effectively confined to a vertical gradient beginning at sea level to about 16,500 ft (roughly 5000 m) in altitude, the rough practical limit of human adaptation for prolonged acclimatization. Simply put, human performance and survivability seem optimized to near sea level conditions.

Nevertheless, humans have now ventured to more than 6 miles (10 km) beneath the surface of the ocean, into near-Earth space, and to the surface of the Moon. Advances in technology and geopolitical relations have enabled large-scale cooperative projects that validate the expectation that humans will travel and live well beyond our traditional narrow envelope. We have adapted to a larger environment and expanded our original sphere of existence. This expansion is a dynamic process that by all indications will continue and probably accelerate as more nations obtain the technology and industrial wherewithal to join this effort. As humans continue to explore and survive in environments that are increasingly beyond standard physiologic limits, an understanding of human reactions to these new environments and development of protective systems and processes becomes more critical. Over the past century, such disciplines as aviation medicine and diving medicine have arisen and matured, playing key roles in expanding human performance and endurance in new environments. These disciplines have successfully fostered the necessary interfaces between physical systems required to support the human aviator or diver and the knowledge of physiology and practice of medicine in these environments. To this same end, keeping pace with current efforts in space exploration, the field of space medicine is emerging and broadening as a distinct discipline.

Aviation medicine, diving medicine, and space medicine all involve pressure excursions, operational changes in body attitude and position, novel motion environments, controlled breathing sources, and critical dependence on supportive mechanisms and protective equipment. Many of the basic problems of space medicine—hypoxia, dysbarism, thermal support, moderate levels of acceleration, and response to unusual altitudes—had been studied over the course of decades of aviation and high-altitude balloon flight and were fairly well understood before the first human space flight ever took place. A basic working knowledge of aviation medicine and physiology remains a fundamental requirement of the space medicine specialist. A thorough review of these basics or of atmospheric science is beyond the scope of this chapter; the interested reader is referred to the sources in the Suggested Reading section at the end of this chapter.

This book focuses on the unique medical circumstances and clinical problems associated with excursions outside of Earth's atmosphere. These circumstances include a wide range of acceleration forces, adaptive processes and problems associated with weightlessness and partial gravity fields, radiation, excursions to other planetary bodies, and biotechnical problems associated with life support systems in enclosed environments. This chapter provides an overview of the basic physics of space flight and physical conditions faced by human space travelers that influence their physiologic responses and adaptation.

M. R. Barratt (✉)
NASA Johnson Space Center, Houston, TX, USA
e-mail: michael.r.barratt@nasa.gov

M. R. Barratt et al. (eds.), *Principles of Clinical Medicine for Space Flight*, https://doi.org/10.1007/978-1-4939-9889-0_1

General Physics of Human Space Flight

Where Space Begins

A singular definition of *space* is elusive and somewhat arbitrary in terms of a specific border or limit relative to the surface of Earth; the definition varies with the particular parameter being assessed. For example, the pressure limit for maintaining body fluids in a liquid state (a physiologic limit) occurs at a specific altitude (about 12 miles/19 km), whereas the rough limit at which forces between aircraft or spacecraft surfaces and the atmosphere support effective aerodynamic control (a physical limit) is quite different (about 62 miles/100 km). The common factor for most biophysical parameters in defining a limit is a threshold degree of removal from nominal atmospheric gas composition and pressure and for mechanical parameters a threshold reduction in density leading to, for instance, absence of aerodynamic lift and drag.

Fifty years ago Hubertus Strughold [1], in a classic and insightful treatise on the interface between Earth and space, described three major atmospheric functions that serve as base points for understanding these limits: (1) the function of supplying breathing air and climate; (2) the function of supplying a filter against cosmic factors (e.g., ionizing radiation, ultraviolet light, meteoroids); and (3) the function of supplying mechanical support to an aircraft. Each of these functions can be further stratified into specific limits and borders. Figure 1.1 and Table 1.1 depict and list several of these limits and physiologic milestones as one ascends vertically through the atmosphere [2–4]. Most familiar weather phenomena occur in the troposphere; it and other discernible boundaries are defined largely by atmospheric heating profiles. Altitudes and temperatures vary somewhat with solar cycle and influences on atmospheric heating. For astronauts flying to low Earth orbit (LEO), all of these limits and zones are traversed in a relatively short time, on the order of several minutes. The flight crew is of course enclosed in a highly protective and controlled environment; however, knowledge of these limits remains important with regard to mishaps that might occur at any altitude during ascent or descent and also defines the capabilities of protective and emergency systems.

Leaving Earth

In the process of launching to a sustainable orbit, a lofting force must be applied that exceeds the gravitational force on the mass to be delivered. In the history of space flight thus far, this force has been provided by chemical rockets, which typically combine a fuel and oxidizer at high temperatures and pressures to create a reactive force through rapid combustion and high-speed expulsion of exhaust products. The hazardous aspects of these systems, with highly explosive mixtures flowing through conduits at extremes of material and hardware performance limits, are obvious. Engine performance is described in terms of two basic parameters—*thrust* and *specific impulse* [5]. Thrust (*F*) is the amount of force applied to a rocket based on expulsion of exhaust gases. In simplified form:

$$F = \dot{m}V_e \tag{1.1}$$

where F is force in Newtons (N or m/kg/s^2), $\dot{m}$ is mass flow rate of propellant (in kg/s), and V_e is exit velocity of the propellant (in m/s). Thrust increases with the product of combustion chamber temperature and the ratio of combustion-chamber pressure to nozzle-exit pressure. Thrust is usually expressed in Newtons (N) or pounds of force (lbs). The five large kerosene and liquid oxygen F1 first-stage engines of the Apollo Saturn V vehicle each supplied 6.7 million N (1.5 million lbs) of thrust. Each of the three Space Shuttle main engines, fueled by liquid hydrogen and liquid oxygen, generated 1.67 million N (375,000 lbs) of thrust at sea level. These were augmented by two large solid fuel strap-on boosters, each with a thrust of 13.8 million N (3.1 million lbs) and burning for a little over 2 min, with the main engines completing the nearly 9-min ascent. The much lighter Soyuz, with the most extensive flight history and reliability record of any human carrier, makes use of four RD-107 engines at lift off, each with a thrust of about 813,000 N (183,000 lbs), as well as a concurrently burning second-stage RD-108 engine with a thrust of 779,000 N (175,000 lbs).

Specific impulse (I_{sp}) is the ratio of the thrust F to the weight flow rate of propellant:

$$I_{sp} = F / \dot{m}g \tag{1.2}$$

Substituting for F in Eq. (1.1) above:

$$I_{sp} = V_e / g \tag{1.3}$$

where I_{sp} is specific impulse (in seconds), F is thrust in N, $\dot{m}$ is propellant mass flow rate (in kg/s), V_e is the exit velocity of the propellant (in m/s), and g is gravitational acceleration at Earth's surface, 9.81 m/s^2. I_{sp} is thus a measure of the exhaust velocity. I_{sp} is proportional to the square root of combustion-chamber temperature divided by the average molecular weight of combustion products and provides a measure of the energy content and thrust conversion efficiency of the propellant. Using a propellant with low molecular mass such as hydrogen or increasing the temperature of the propellant will serve to increase I_{sp}. I_{sp} can also be defined as the time (in seconds) required to burn 1 kg of propellant in an engine producing 1 N of force. As a point of reference, the Space Shuttle main engines were among the most efficient

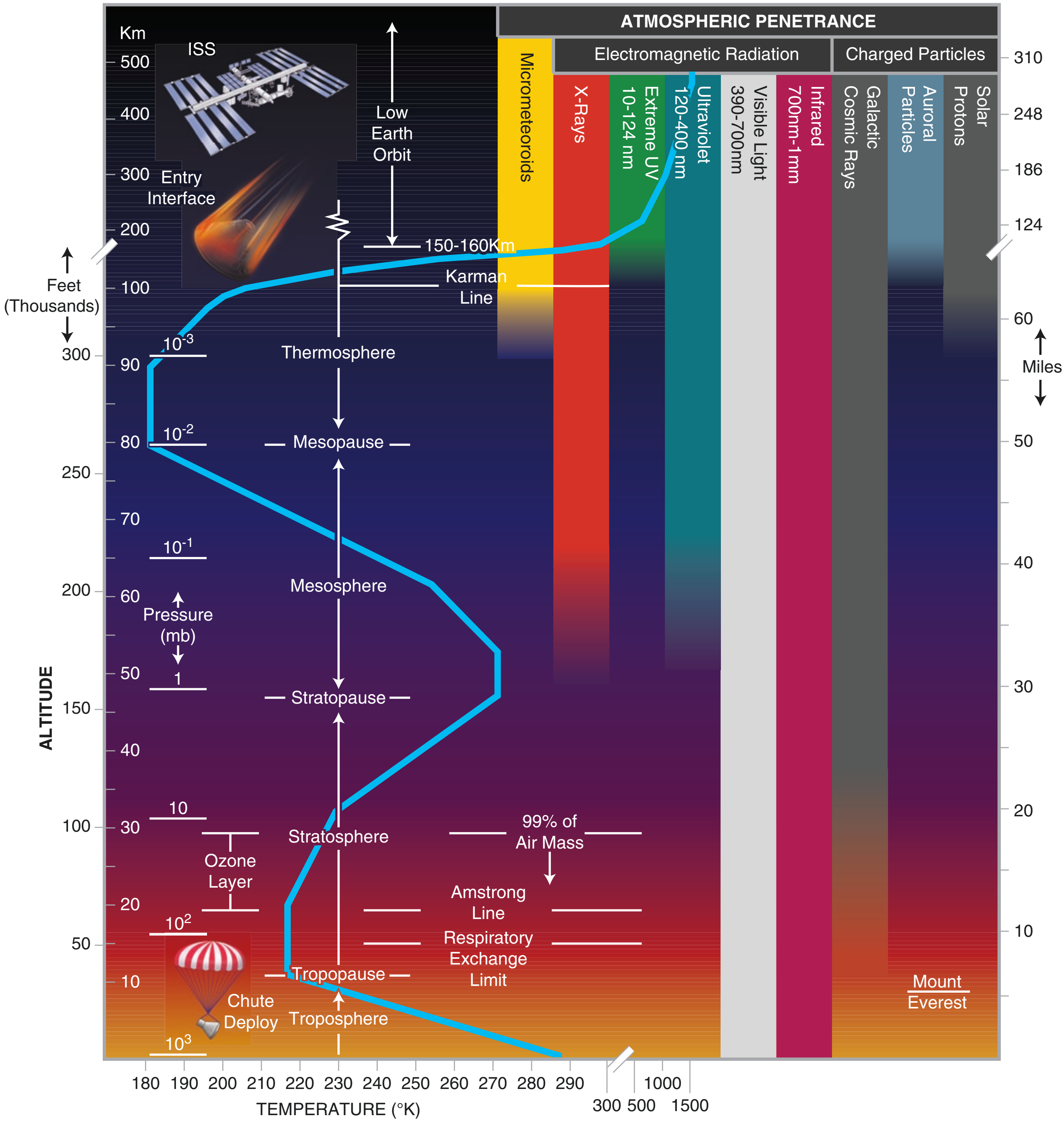


Fig. 1.1 Temperature, pressure, and penetrance characteristics of the atmosphere with increasing altitude. For context, the International Space Station orbits at roughly 250 miles (400 km). A reentering spacecraft first encounters atmospheric forces at entry interface, roughly 74 miles (120 km). Initial drogue chutes may deploy below 50,000 ft (15 km) to slow a spacecraft down and transition to vertical descent under large main chutes. Depictions of penetrance of micrometeoroids, electromagnetic radiation, and charged ion particles emphasize the shielding aspects of Earth's protective atmosphere. (Radiation penetrance values from NASA Goddard Space Flight Center. Ft (thous) thousands of feet, Km kilometers, mb millibars, ISS International Space Station.) (From [2])

chemical rockets developed, with a vacuum-rated I_{sp} of 452.5 s. The shuttle's solid rocket boosters had a vacuum-rated I_{sp} of 267.3 s [6].

The classic rocket equation, first described by William Moore in 1813 [7] and independently derived and refined by others afterward, relates rocket performance to the frequently used metric of "delta v," or Δv. This is the change in velocity of a vehicle realized by expelling part of its mass, typically fuel in the form of engine exhaust. For a given spacecraft maneuver, this may be expressed as:

Table 1.1 Physical and physiological milestones during the transition from the Earth surface to space.

Altitude	Event or limit
192,000 km (120,000 miles)	Upper limit of exosphere; gravitational pull on atomic hydrogen is exceeded by pressure of solar wind
700 km (440 miles)	Exobase, lower limit of exosphere, and border of atmosphere above which barometric conditions no longer apply; molecules still gravitationally bound but collisions with other molecules too low for behavior as gas. Altitude ranges from 500 to 1000 km, increasing with solar activity. Particle density gradually diminishes over thousands of km to free space density of 1–10 per cc, mostly atomic hydrogen
400–410 km	International Space Station
200 km (124 miles)	Essentially no aerodynamic support; sustainable orbital altitude
150 km (96 miles)	Aerothermodynamic border; minimal aerodynamic resistance or structural heating. Practical limit of low Earth orbit (LEO)
140 km (87 miles)	Meteor safe zone limit; above this insufficient atmospheric density to effectively stop entry of micrometeorites
120 km (75 miles)	The so-called atmospheric entry interface for returning spacecraft; initial onset of perceptible acceleration forces, control surface resistance. Dysacoustic zone; insufficient atmospheric density to facilitate the effective transmission of sound
100 km (62 miles)	Minimal atmospheric light scattering, "blackness of space"; Karman line, threshold of effectiveness of aerodynamic surfaces
80 km (50 miles)	US Air Force awards astronaut status
45 km (28 miles)	Little protective ozone. (Ozone layer about 10–40 km)
40 km (24.9 miles)	Atmosphere ceases to protect objects from high-energy radiation particles
25–30 km (15.5–18.6 miles)	Practical limit of ram-pressurized cabin; above this altitude, fully enclosed pressurized cabins are required
20–30 km (12–18.6 miles)	Main concentration of ozone
19,200 m (63,000 ft)	"Armstrong's line"; Ambient pressure = 47 mmHg, equivalent to tension of water vapor at body temperature. Above this altitude, body fluids vaporize
16 km (10 miles)	Practical limit of atmospheric weather processes and phenomena at equator (the altitude is lower near the poles)
15,240 m (50,000 ft)	Respiratory exchange limit; ambient pressure = 87 mmHg, equivalent to sum total of alveolar water vapor tension (47 mmHg) and CO_2 tension (40 mmHg). No respiratory oxygen exchange is possible. Pressure suit or pressurized cabin is required
10,400 m (34,000 ft)	Practical limit for breathing 100% O_2 in an unpressurized cabin. Above this altitude, positive pressure breathing is required to maintain normoxia. Ambient pressure = 187 mmHg; PAO_2 on 100% O_2 = 100 mmHg
8850 m (29,035 ft)	Elevation of Mt. Everest, high point on Earth
4570 m (15,000 ft)	Approximate upper limit of human acclimation; PAO_2 = 45 mmHg breathing ambient air. Supplemental oxygen is required if not in pressurized cabin
3048 m (10,000 ft)	US Air Force requires that pilots breathe supplemental oxygen. PAO_2 = 60 mmHg if breathing ambient air
1525–2440 m (5000–8000 ft)	Cabin pressure of commercial air carriers; PAO_2 = 81–69 mmHg
Sea level	Pressure 760 mmHg/14.7 psi. Reference PAO_2 = 100 mmHg

PAO_2 alveolar oxygen tension

$$\Delta v = v_e \ln\left(m_1 / m_2\right) \tag{1.4}$$

where Δv is change in vehicle velocity for the maneuver, v_e is exhaust velocity, m_1 is total mass (vehicle + fuel) at start of maneuver, and m_2 is total mass at end of maneuver. (ln is the natural logarithm function.) As for the description of I_{sp} above, the classic rocket equation highlights the influence of exhaust velocity on engine performance.

Limitation of engine performance is arguably the most important factor currently influencing space exploration. This affects the amount of payload that can be delivered to orbit and the payload mass and velocity that can be directed to a distant site out of LEO. For a given spacecraft, the ultimate measure of overall performance is its capability to provide the Δv required for a complete mission profile. This includes launch to orbit, in which the required Δv is the difference between the velocity component of Earth's rotation in the desired orbital plane and the final orbital velocity. It also includes losses from drag and gravity while traversing the atmosphere en route to orbit, as well as subsequent changes in orbital altitude and plane and potentially escaping from Earth orbit. For launching to orbit, provision of sufficient Δv for a given payload depends greatly on the engine efficiency and the amount of propellant. To gain an appreciation of the relationship between payload, spacecraft structure, and propellant, it is instructive to examine the mass fractions of a standard Earth-to-orbit spacecraft. Typical values for propellant, structural, and payload mass fractions are 0.85, 0.14, and 0.01, respectively [8]. The Saturn V Apollo lunar vehicle had a total launch weight of 2,621,000 kg. Of this, 129,250 kg (4.9%) was delivered to LEO, but only 45,350 kg or about 1.7% was accelerated to escape velocity away from the Earth toward the Moon [9]. After the lunar mission was completed, including crew descent to the surface and subsequent shedding of the lunar module, the final reentry weight of the command module carrying the crew

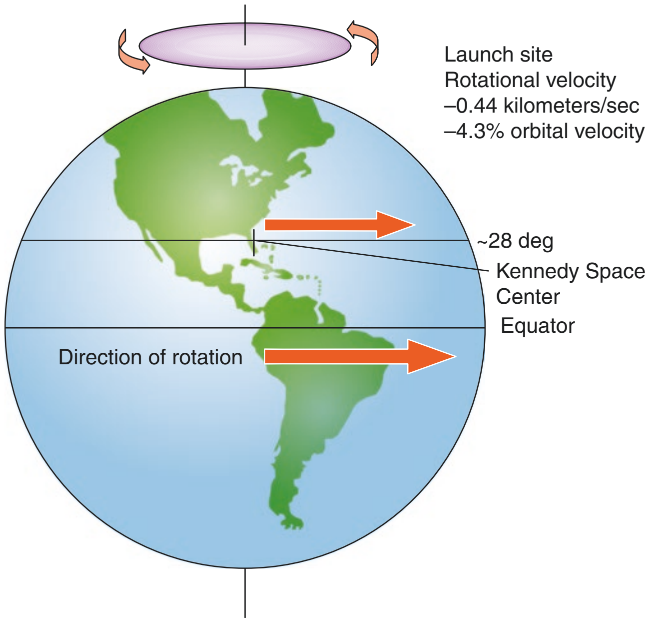


Fig. 1.2 Velocity assist from Earth's rotation for eastward (posigrade) launch. Note that the line at 28° represents the vector component of the velocity assist, not the resulting orbit which must necessarily circle Earth's center of mass.

and lunar sample material was only about 5670 kg—roughly 0.2% of the original launch weight.

For initial launch to orbit, the velocity component of Earth's rotation can provide a significant boost in Δv. Such a boost is best afforded by launching directly along the rotational velocity vector, or straight eastward (Fig. 1.2). Practically, launch from the equator eastward would provide an additional 1600 kilometers per hour (1000 mph) in "free" Δv, or nearly 6% of final Δv required to achieve LEO (roughly 8 km/s), translating into enhanced system performance and increased payload. Thus launching from higher latitude sites, or for any given site launching to azimuth angles higher than the latitude, translates into degraded performance and diminished payload-to-orbit capability. To date, all crewed launches to LEO have involved eastward or *posigrade* launches in the direction of Earth's rotation. The US Space Shuttle, launching from the Kennedy Space Center at about 28° north latitude, attained its maximum performance by launching directly eastward over the Atlantic Ocean. In doing so, the shuttle achieved an orbit of 28° of *inclination*, defined as the angle between Earth's equatorial plane and the plane of the spacecraft's orbit (Fig. 1.3). An Earth orbit must necessarily define a plane with the gravitational center roughly in the middle; therefore for a given launch site, launching straight eastward attains an orbital inclination equal to the launch site's latitude. A vehicle can launch to a higher inclination while losing some of Earth's rotational velocity advantage. To illustrate a range of possible inclinations, Space Shuttle missions varied from minimum inclinations of 28.35° to a maximum of 62°, the latter extreme during STS-36, a Department of Defense mission.

The inclination of the desired orbit cannot be lower than the launch site latitude without a significant performance penalty; in such a case, the ground site never rotates through the orbital plane, and no practical launch windows exist. Posigrade launches from NASA's Kennedy Space Center site in Florida are constrained to orbital inclinations 28° and above, whereas launches from the Russian launch site in Baikonur, Kazakhstan, are restricted to inclinations at or above the site latitude of about 46°. Geopolitical constraints prohibit straight-east launches from Baikonur (to avoid dropping spent stages on Chinese territory), further limiting the effective inclination. A practical implication of this fact is that target orbits for large-scale projects involving multiple launch facilities are limited by the facility located at the highest latitude. For this reason, the orbital inclination of 51.6° for the International Space Station (ISS) is defined by the Russian launch, range, and tracking capabilities and must be accommodated by the lower-latitude US, Japanese (Tanegashima, 31° latitude), and European (located in Kourou, French Guiana, at 6° latitude) launch sites. The Chinese man-tended stations Tiangong-1 and Tiangong-2 were launched from the Jiuquan launch complex located in the Gobi Desert at about 41° north latitude into a 42.8° inclination orbit. Crews flying the Shenzhou spacecraft have launched from this same complex to rendezvous with these orbiting platforms.

The most flexible launch site in terms of access to the widest range of orbital inclinations would be located near the Equator. The European Space Agency operates a launch facility in Kourou, French Guiana, situated at 6° north latitude, and China has recently completed the Wenchang launch complex on the island of Hainan at about 19° north latitude. An elegant although logistically complex approach to maximizing performance is to position a mobile seagoing launch platform at the equator when launch ready, as was realized by the Sea Launch System. One other key consideration for orbital inclination is that for a given orbital altitude, higher-inclination orbits, although deriving minimal launch benefits from Earth's rotation, cover more of Earth's surface in their ground track, a situation that influences Earth observation and direct access to ground communication facilities.

The desired orbit to which a spacecraft is lofted is said to be fixed in *inertial* space rather than relative to ground surface features; the central point of reference is the gravitational center of the Earth. The motion of the orbiting spacecraft becomes indifferent to the Earth-surface features rotating beneath it. A reference system independent of Earth-surface features is needed to describe orbital motion; as such, an inertial coordinate system has been adopted that characterizes the basic elements of an object's orbit. This system is based on a *geocentric* or *Earth-centered inertial* model,

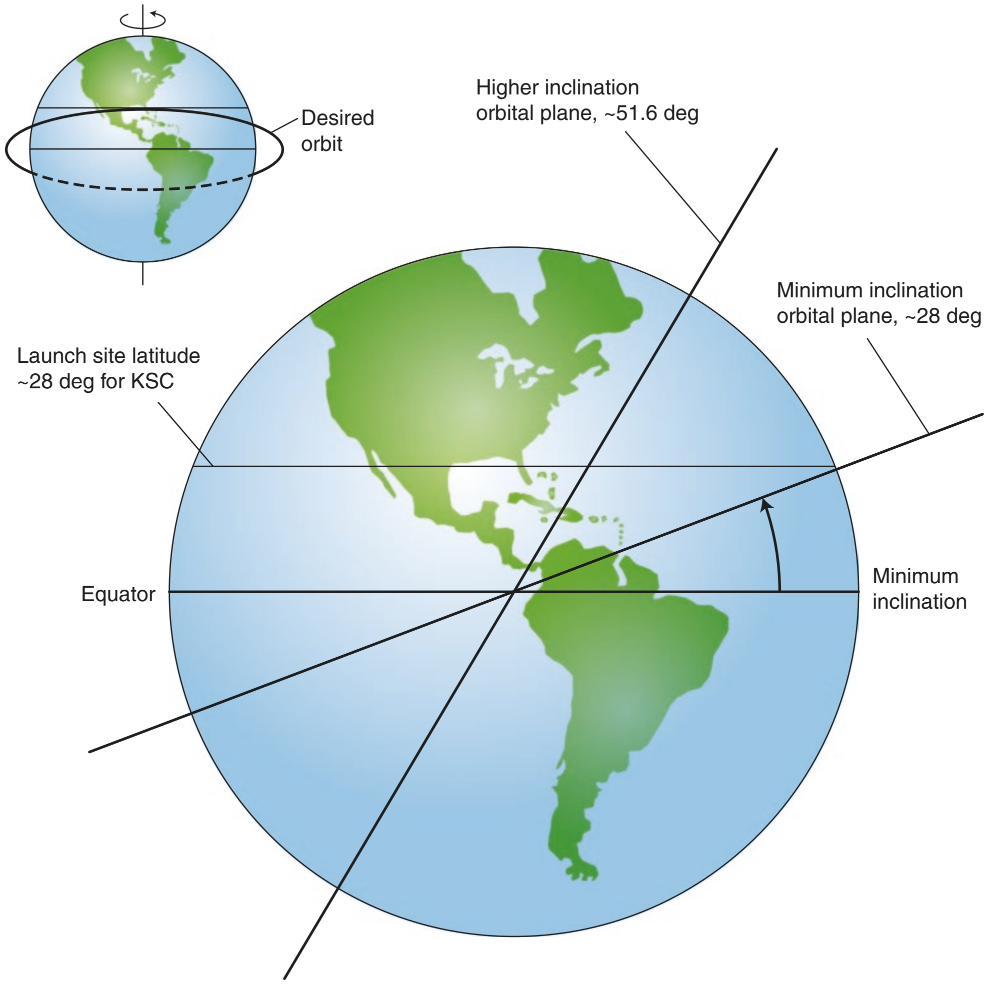


Fig. 1.3 Orbital inclination, the angle between the orbital plane and Earth's equatorial plane. For any launch site, the minimum achievable inclination is equal to the launch site's latitude. Higher-inclination orbits are mechanically achievable but obtain less advantage from Earth's rotation.

which places the gravitational center of Earth at the origin of a three-axis system (Fig. 1.4). The plane of Earth's equator contains two perpendicular axes, X and Y. The Z-axis extends through the axis of rotation, and X points toward a fixed position in space, the vernal equinox or First Point of Aries defined for the year 2000. The Y-axis completes a right-handed coordinate system. Because the Earth's rotational axis precesses over time due to irregularities in its mass distribution, the position in space defined by the equatorial and ecliptic planes at the vernal equinox varies over time and must be periodically updated. The so-called J2000 reference system is currently in use, having replaced the M50 coordinates for which X was defined as the vernal equinox for the year 1950.

The most efficient insertion into a desired orbit comes about by lofting from the launch site, which is fixed relative to the ground, directly into the desired orbit. Missions involving rendezvous and docking with another orbiting spacecraft require synchrony between launch time and the target object's motion. This requirement gives rise to *launch windows*, spans of time during which the launch site rotates

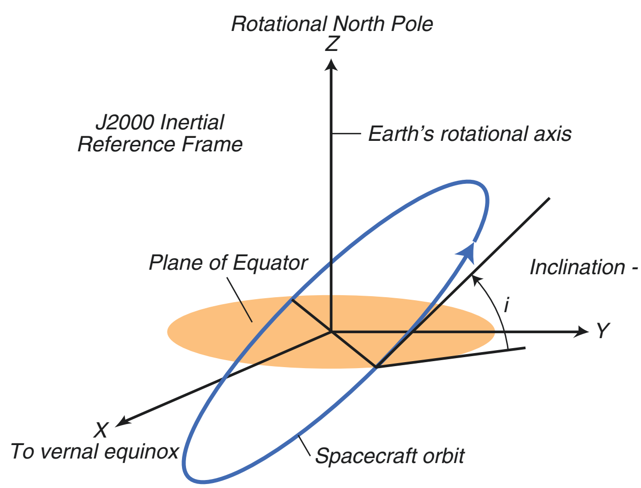


Fig. 1.4 The J2000 Inertial Reference Frame. With Earth at the center (geocentric), the Z-axis points through the rotational North Pole, the X-axis lies in the plane of the equator and points toward the vernal equinox (First Point of Aries) for the year 2000, and the Y-axis passes through the equatorial plane to complete a right-handed coordinate system. The inclination of a spacecraft's orbit is the angle between the orbital plane of the spacecraft and the Earth's equatorial plane.

through the target orbital plane. Thus the time of the launch depends on the latitude and longitude of the launch site and the desired orbit's plane and inclination. Launch opportunities may exist for both ascending (northbound) and descending (southbound) legs of the orbit. Higher-inclination orbits imply steeper intersect angles between the launch site velocity vector from Earth's rotation and launch azimuth as well as shorter launch windows. For a spacecraft launching straight eastward from the Kennedy Space Center at a latitude of 28° with no rendezvous requirements, a launch window is not constrained by orbital mechanics and may last several hours, limited only by vehicle or crew readiness. By contrast, when launching from that site to a high-inclination rendezvous orbit, such as to the 51.6° ISS orbit, the launch window effectively becomes 5–10 min long given current performance limitations. Little margin exists for steering sideways to intercept an orbital plane if the optimal launch time is missed. Adverse weather conditions or hardware anomalies during the period immediately before launch that require assessment and timely action by the ground team thus can have a more profound effect on the success of launches that attempt to reach higher-inclination rendezvous targets.

Other launch-window determinants include constraints of lighting from the angle of the Sun, the flight path over ground sites during critical activities, planetary geometry for transplanetary flights, and crew factors such as time spent in the launch position in full launch suit and rescue gear and crew duty day. For flights that do not involve rendezvous, lighting and crew physical and duty limits become the primary factors determining the duration of the launch window.

For a given orbit, the launch window timing changes from day to day as Earth rotates eastward independent of the inertial orbital plane. There are two points or nodes of an orbit, points at which it crosses the equator. Typically the ascending node of an orbit is used as a reference point, and for a *posigrade* launch, that is in the direction of Earth's rotation, this node can be seen to track westward for a given clock time relative to the day before. This phenomenon, known as *nodal regression*, is due primarily to the oblate nature of Earth induced by the equatorial bulge. The combination of nodal regression and Earth's rotation beneath an orbit causes the launch site to rotate through the orbital plane earlier on successive days. For a planned launch from Kennedy Space Center to the 51.6° ISS orbit, for example, missing a launch opportunity because of weather or mechanical factors results in the next day's opportunity being approximately 20 min earlier than on the planned day. This time accumulates over a delay of several days, and such a delay may require shifting the crew's sleep period if the crew is adapted to a certain operational time schedule.

Earth Orbit

In attaining orbit, the influence of aerodynamics on a spacecraft and its crew becomes negligible, and the influence of the basic laws of Newtonian mechanics dominates. Weightlessness (or free fall) is sustained when the inward force of gravity is exactly counterbalanced by the outward centrifugal force on the spacecraft, with sufficient velocity forward to result in a flight path tangential to the surface of Earth. For a circular orbit, the flight path becomes a constant altitude; for an elliptical orbit, the altitude will vary depending on relative position on the orbital track. To be sustainable, the altitude must be sufficient to escape drag-inducing atmospheric interaction, and forward (tangential) velocity must be high enough to keep the spacecraft falling around Earth rather than to Earth; this is the state of *free fall*, which is perceived as weightlessness. The standard orbital velocity in LEO altitudes associated with human flight is roughly 5 miles/s (8 km/s); sustaining orbital velocities are progressively lower with increasing altitude. A typical Space Shuttle mission was flown at an altitude of 200 miles (320 km) with a forward velocity of 17,500 mph (28,160 km/h). The ISS orbits at an average altitude of about 250 miles (405 km), with a forward velocity of 17,200 mph (27,600 km/h).

Even at these altitudes, over time atmospheric drag is sufficient to cause orbital decay. Solar magnetic activity is dynamic along short-term spikes and in long-term cycles, driving effective thermal expansion of the atmosphere and increasing its resulting drag on an orbiting spacecraft. A large orbiting platform thus requires periodic reboosting to remain in orbit. The ISS, with a large cross-sectional area, requires several thousand kilograms of propellant per year to perform altitude reboosts. Less propellant is needed to maintain higher orbits, but lower altitudes are maintained as needed to match performance of visiting vehicles. Figure 1.5 shows a reboost profile over time of the ISS. Decreasing the cross-sectional area of the craft relative to the velocity vector, which can be done by feathering solar arrays or changing the structure's attitude, may serve to decease drag and maintain orbital altitude for longer periods.

The orbital shape of an object gravitationally held by Earth is typically elliptical, with two major landmarks: the *perigee*, the point along the elliptical path closest to Earth's center, and the *apogee*, the corresponding point farthest from the center. The complete characteristics of a spacecraft's orbit can be defined by six primary factors, or *orbital elements*. Also known as the classic Keplerian elements, these elements are based on a three-axis reference system using Earth's center as an inertial origin point.

Figure 1.6 describes the basic elements of a body in orbit. The Z-axis is the Earth's axis of rotation and goes through

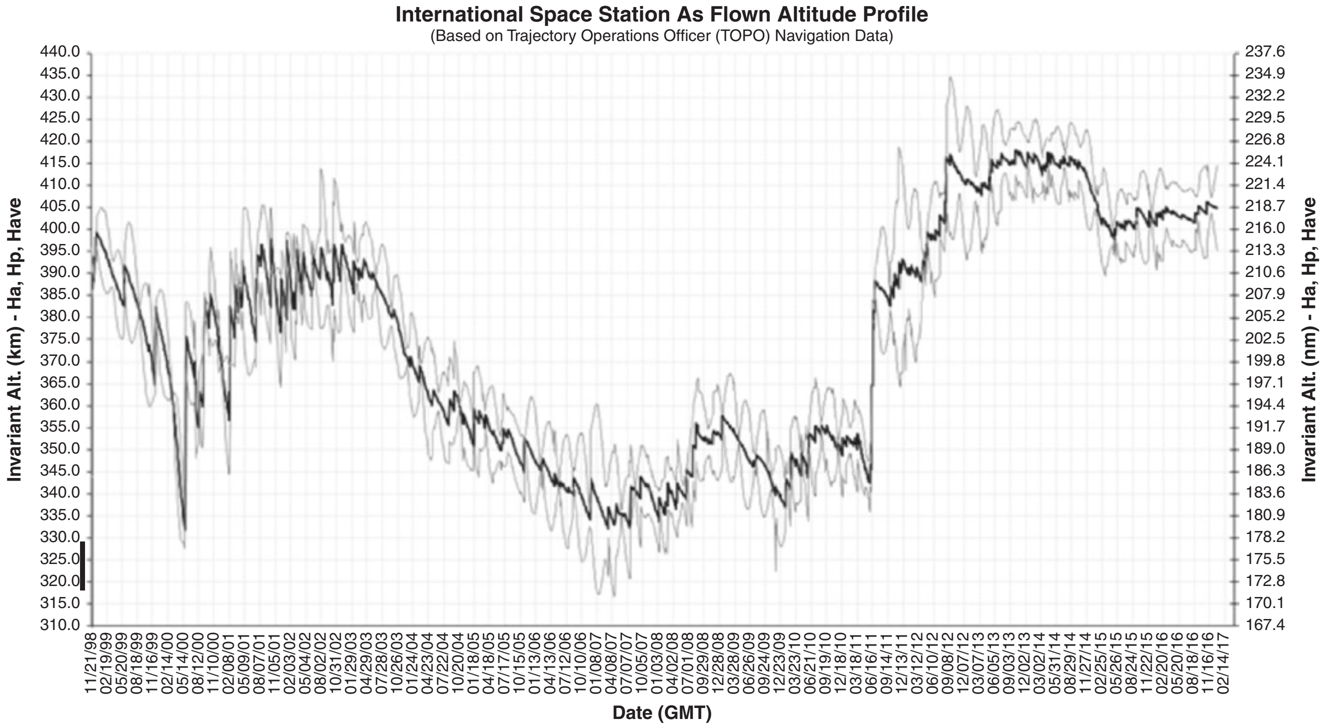


Fig. 1.5 International Space Station altitude profile from first element launch in 1998 through 2017. Atmospheric drag continually degrades the orbit causing lowering of altitude. Sharp up-spikes represent powered reboost maneuvers. The sharp altitude rise in 2011 reflects the end of the Shuttle program and represents a 29.5-mile (47.5-km) altitude increase with a delta V of 88 ft/s (27 m/s) and costing 3700 kg of propellant in a short series of reboost engine burns.

the north (+Z) and south poles. The X- and Y-axes are in the equatorial plane, with +X pointing to the vernal equinox and +Y offset 90° in a right-handed system. The following elements are required to completely describe an orbit for a two-body system [10]:

a:	*Semi-major axis*: describes the size of the ellipse (Fig. 1.6a)
e:	*Eccentricity*: describes the shape of the ellipse (Fig. 1.6a)
i:	*Inclination*: the angle between the angular momentum vector and the unit vector in the Z-direction (Fig. 1.6b)
Ω:	*Right ascension of the ascending node*: angle from the vernal equinox to the ascending node. The ascending node is the point where the satellite passes through the equatorial plane moving south to north. Right ascension is measured as a right-handed rotation about the pole, Z (Fig. 1.6b)
ω:	*Argument of perigee*: the angle from the ascending node to the eccentricity vector measured in the direction of the spacecraft's motion. The eccentricity vector points from the center of the Earth to perigee with a magnitude equal to the eccentricity of the orbit (Fig. 1.6b)
ν:	*True anomaly*: the angle from the eccentricity vector to the satellite position vector, measured in the direction of satellite motion. This is a time component; alternatively, time since perigee passage could be used

The precise orbit of a spacecraft may not be completely described with these classical elements because of various perturbation forces such as third-body effects (e.g., lunar gravitational influence), solar radiation, atmospheric drag, and the influence of a non-spherical Earth. Although the effects of these perturbation factors are smaller than those of the basic elements for a spacecraft in LEO, the perturbation factors must nevertheless be accounted for in mission operations. Detailed descriptions of the classical elements and other factors are beyond the scope of this text; however, the basic understanding of these factors is useful for the space medicine specialist's situational understanding of crewed space flight.

After launch and ascent, which typically lasts 8–9 min, a crewed spacecraft such as the Soyuz or Space Shuttle quickly traverses the atmosphere and realm of aerodynamics into LEO. The path of a spacecraft over the ground (its *ground track*) can be envisioned by flattening out Earth's spherical shape, thus producing the familiar sine wave track over the Mercator projection maps used in mission control centers (Fig. 1.7). The 22.5° westward precession of the ground track for each 90-min orbit can be seen as Earth continues to rotate eastward independent of the inertial orbital plane. Thanks to this continued precession, the ISS affords direct view of the entire surface of the Earth between 51.6° north and south latitudes as well as oblique views for a few degrees beyond these bor-

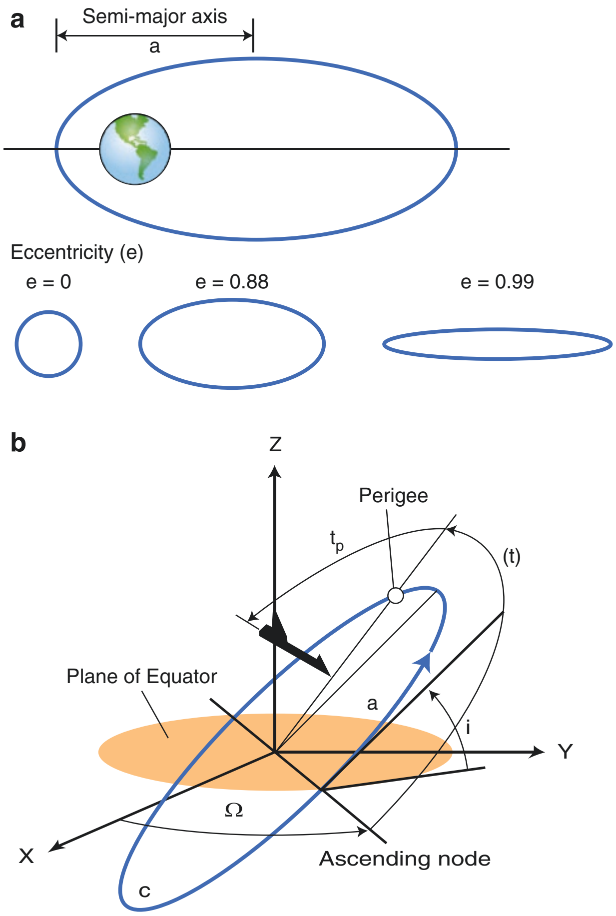


Fig. 1.6 (**a**, **b**) The six primary elements describing a spacecraft orbit. These are known as the classic Keplerian elements and define the size, shape, and orientation of the orbit, as well as the position of the spacecraft on the orbit (see text).

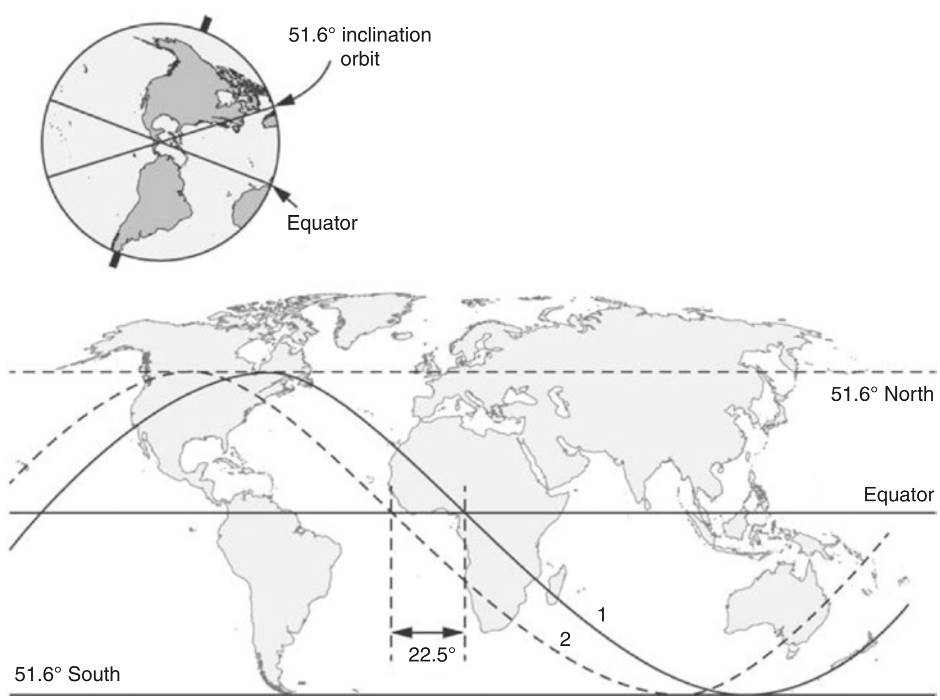
ders, allowing crewmembers and imagery instruments visual access to over 85% of the world's population distribution.

Spacecraft can be placed into a wide variety of orbits, including those involving *retrograde* launches (opposite the direction of Earth's rotation) and *geostationary* positions, which maintain a constant position relative to a fixed ground point. However, the human presence introduces limitations that are based on environmental hazards. For human space flight, LEO is for practical purposes bounded at the lower altitude by the physical constraint of atmospheric interaction and at the upper altitude by the medically hazardous constraint of increasing radiation exposure from the geomagnetically held Van Allen radiation belts. These constraints result in the standard LEO altitude envelope for long duration flight being between 124 miles (200 km), below which atmospheric drag would cause rapid decay of the spacecraft orbit, and approximately 312 miles (500 km), where depending on orbital inclination the daily ionizing radiation dose becomes excessive for long duration missions. The relationship of orbital characteristics and radiation exposure is described further in Chap. 2.

Suborbital Space Flight

Some of the earliest encounters of humans in the spaceflight environment involved suborbital flights as high atmosphere and spaceflight systems were being developed and incrementally tested. These included two piloted Mercury-Redstone missions and two using the high altitude air-launched X-15 rocket plane. By convention suborbital space flight involves

Fig. 1.7 Ground track of a spacecraft in low Earth orbit, in this case the International Space Station with an orbital inclination of 51.6°.



a trajectory that exceeds the internationally recognized limit of the Karman line in altitude, roughly 60 miles (100 km), but does not attain sufficient velocity (dV) to sustain orbit. Suborbital flight profiles can take many forms, from a high-lofting intercontinental ballistic missile that may reach over 600 miles (1000 km) in altitude before intercepting Earth's atmosphere thousands of miles down range to a more limited vertical loft that just exceeds the Karman line and returns to a point near the launch site. These profiles involve a period of free fall, between cutoff of ascent engines and the point of atmospheric entry. Between these milestones the spacecraft may continue to coast upward to apogee before beginning to fall back to Earth, with weightlessness ending as acceleration loads build from atmospheric resistance. Figure 1.8 shows the flight profile of the second piloted Mercury-Redstone flight. With a maximal altitude of 102.8 nautical miles (190 km), this profile afforded about 5.5 min of weightlessness, interrupted by a brief engine retrofire [11].

A newly rising suborbital tourist industry is on the verge of affording a wide population range with a spaceflight experience, using both air-launched winged vehicles and more conventional ground-launched capsules with parachute landing systems. These will offer the experience of a rocket-powered ascent beyond the internationally recognized border of space, several minutes of weightlessness during the free fall stage, and panoramic horizon views that in the past were available only to professional astronauts. This will also create affordable access for autonomous and tended science packages that can utilize brief periods of sustained weightlessness.

Orbital Debris

Early seafarers had to contend with uncharted reefs and occasional large floating debris; space vehicles in LEO are faced with an analogous collision potential. Operations in Earth orbit can bring spacecraft near other gravitationally held objects, primarily originating from artificial sources. Given the standard orbital velocities of such objects and assuming unlimited radical orbital paths, the collision velocities can be formidable, with an average relative velocity between two objects of 6 miles/s (10 km/s); with this relative velocity, a 100-g fragment possesses kinetic energy equivalent to 1 kg of TNT [12].

The vast majority of the material in LEO is artificial, consisting of active spacecraft, spent and inactive satellites, booster components, and fragmentation products resulting from pyrotechnic separation devices and spacecraft collisions. Most of these are metallic fragments with an average density of aluminum (2.7 g/cc^3). More than 95% of tracked objects are considered unusable debris. The more heavily used orbits tend to be the most cluttered with debris. In contrast, the flux of natural material, consisting mostly of fragmentation and disintegration products of comets and asteroids, is much lower than that of artificial material. Natural material flux is primarily confined to particles smaller than 1 mm with greater average velocity compared with artificially orbited debris fragments, up to 70 kps. Such particles continually rain down on Earth and rarely slow enough to become trapped in LEO. One estimate based on impact craters accumulated on the Long Duration Exposure

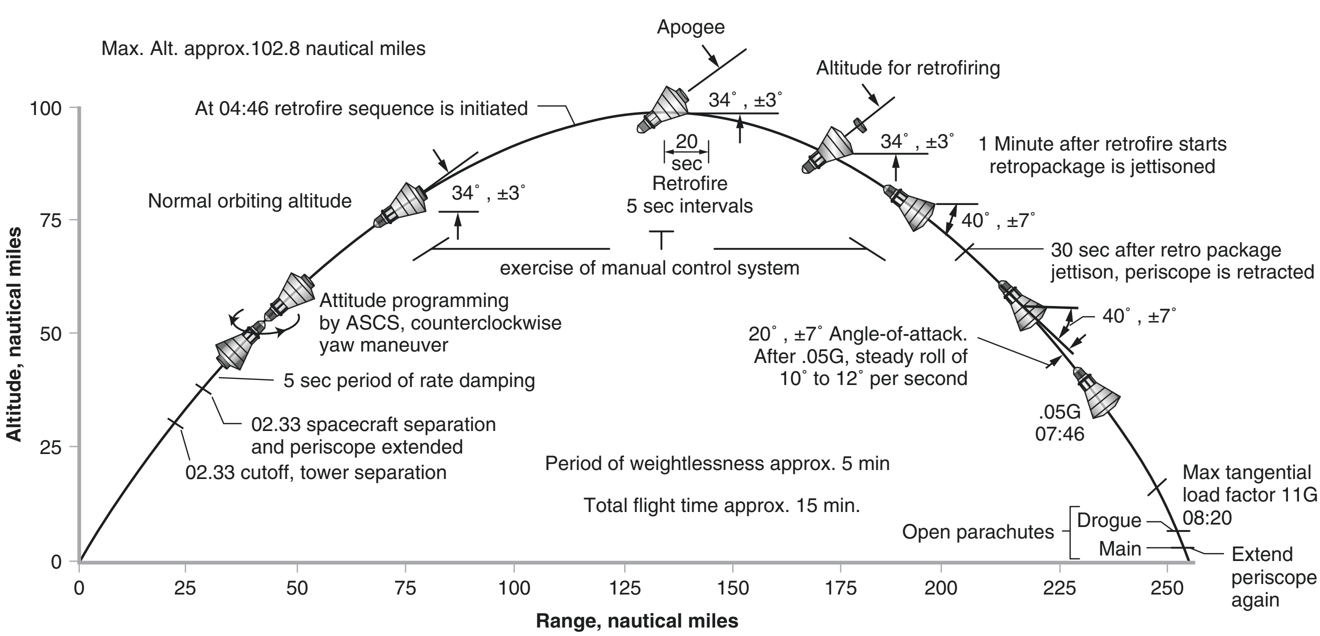


Fig. 1.8 Flight profile for the suborbital Mercury-Redstone 4 flight, July 21, 1961, carrying astronaut Virgil Grissom. *ASCS* automatic stabilization control system. (From [11])

Facility over its nearly 6-year residence in LEO is that approximately 40 million kg of such matter reaches Earth's surface annually, with the peak in the size distribution at about 200 μm in diameter. This mass amount is thought to be comparable over very long time scales to the contribution from bodies of much larger size (in the 1-cm to 10-km range) [13]. This correlates well with a more recent estimation of 40,000 metric tons per year of meteoritic material reaching Earth, with the vast majority in grains between 10^{-16} and 10^{-4} kg in mass [14].

Orbiting objects are classified by size based on radar visibility and the means to track them [15]. *Small* debris items are less than 1 cm in size and comprise the vast majority of debris pieces by number and cumulative mass. These are essentially invisible to ground radars, and estimates of their numbers are based on known spacecraft operational profiles and exposure data from orbiting platforms. Effective shielding options exist for hypervelocity impacts resulting from this population and are deployed on the ISS to prevent major structural damage. A "smart impact" is possible whereby a fragment in this size range damages a pressure vessel or conduit, electrical cable, or other critical systems, possibly disabling the station. A greater problem in LEO is the surface degradation of structures over time that are slowly sandblasted by fine high-velocity particles. In addition, small pits and craters may be formed that pose a sharp edge hazard to the pressure suits of spacewalking astronauts translating hand over hand along external structures. When these are identified on ISS, they are location marked and covered with tape to protect from glove damage. *Large* objects are greater than 10 cm in size and can be both seen and tracked by ground radar systems below altitudes of 2000 km. Continual surveillance of these objects allows prediction of near conjunctions. For large spacecraft in LEO with propulsive capability such as the Mir and ISS stations and the US Space Shuttle, this affords preventive avoidance maneuvers to be performed, typically involving raising the orbit hours ahead of the near conjunction. *Medium*-sized objects, in the 1–10-cm range, actually constitute the greater risk to LEO platforms. These can be seen but not tracked effectively, so although the risk of collision can be calculated with greater certainty than smaller objects, they cannot be avoided. Shielding options for medium-sized objects are more constrained, becoming unduly prohibitive of material mass and cost to be considered completely protective. Fragments in this size range can inflict considerable damage and pose a real risk for decompression of a habitable module. Currently new radar systems are being developed that will be able to track objects in the range of a few cm in size, which will allow avoidance maneuvers of space platforms for these objects as needed and reduce proximity uncertainty bands for near encounters.

The flux of orbital debris fragments has been steadily increasing, including significant step increases since the first edition of this chapter. A 1997 report cited about 8000 objects in the *Large* category being actively tracked [16]. In 2011, the US Strategic Command reported that over 22,000 objects were being tracked in LEO in this size category [17], and NASA estimated over half a million objects in the *Medium* or larger category populated LEO [15]. Figure 1.9 depicts the rise over time in the number of tracked objects in LEO, showing a nearly linear and parallel relationship over the first several decades of spaceflight activities [18]. Although there had not been documented LEO collisions or other significant

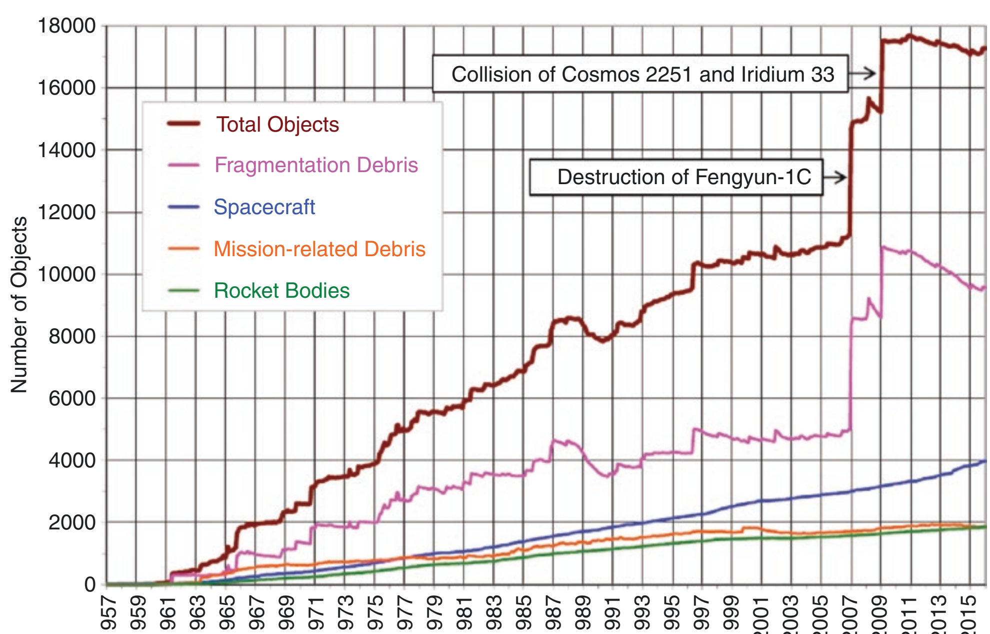


Fig. 1.9 Population over time of tracked orbital debris. Sharp increases in 2007 and 2009 reflect anti-satellite weapon test and random satellite collision, respectively. (From [18])