The Environment of Space Exploration

2

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Chapter Overview

Understanding the nature of the space environment is as important for physicians, astronauts, life scientists, and aeronautical engineers, as it is for planetary and physical scientists. Designing spacecraft, safe crew living quarters, personal protective systems, work procedures, and exploration systems has and will continue to benefit from robotic exploratory missions. Robotic missions inform aerospace engineers as to the function, design and performance of crewed systems for future exploration missions. The complexity of planetary human space missions will continue to increase in the future as we venture farther and for longer periods of time into our Solar System. Practitioners of space medicine must be prepared to use the knowledge gathered from robotic missions to identify challenges and hazards to address the health risks for future human expeditions and potential settlements beyond the confines of the *biosphere*. Future crews' exposure to space hazards, notably radiation, and possibly to new ecosystems, require special and careful planning. The future of human space exploration is coupled with scientific curiosity based on robotic missions and also by the direction provided by the U.S. President's space policy. Commercial aspirations for exploring and prospecting for resources of our Solar System are poorly defined and will require international agreements to be addressed by the United Nations. Astrobiology, planetary protection, and ethical considerations are also discussed. This chapter provides a short review of our Solar System, and discusses prospective destinations, intended to inform physicians, biomedical engineers, and mission planners interested in space medicine. Some of the mentioned destinations are in the planning stages by different space agencies, and by commercial entities. The fields of planetary sciences and space physics continue to make newer discoveries, which might not have been captured in this chapter. For a more in-depth scientific and technical review of our Solar System and the Universe, interested readers should consult appropriate scientific publications.

Learning Objectives

1. Review the Solar System environments, hazards and potential risks to human health.
2. Address the principles of Planetary Protection.
3. Explore theories of the presence of life in the Universe (Astrobiology).

Introduction

> Here Men from the Planet Earth First Set Foot upon this Moon
> July 1969, A.D. We Came in Peace for All Mankind.[1]

Humans are explorers by nature. Technological constraints limit our study of the universe and the solar system to robotic missions and ground and space telescopes. Exploration of our Solar System is of scientific, commercial, and humanity's survival interests. The Universe's vast expanses, separating stars, and galaxies are filled with matter subjected to four universal forces (Table 2.1) [1–3]. Human exploration of the Solar System is planned for the mid twenty-first Century (Box 2.1). On November 5, 2015, NASA announced a call for astronaut applicants for long duration missions on the International Space Station (ISS) and possible journey to Mars, using commercial spacecrafts. As of 2016, only one nation has sent its astronauts to explore the Moon.

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[1] The words on a plaque left on the Moon by Apollo 11 Astronauts Neil Alden Armstrong and Edwin Eugene "Buzz" Aldrin, Jr. The words are from the National Aeronautics and Space Act of 1958.

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Table 2.1 Summary of the current and theoretical understanding of the physical fundamental forces[a] (see also ref. [3] for additional information)

Force (interractions)	Explanation/*mediator*	Physical and/or health effects
Strong nuclear	Acts over a short distance of 10^{-15} cm, and only affects matter carrying electrical charge/*gluon*. Strenght is 1	Holds atoms together, usually attractive but can be a repulsive force. Adequate evidence for health effects is lacking
Electromagnetic	Long range (infinite). Strength is 1/137	Can be attractive or repulsive (as in magnets), and acts on matter particles carrying electric charges. Can cause radiation damage if accompanied by high energy particles [1]. Involved in the depletion of the Earth's ozone layer [2] Does generate heat and may cause brain damage (good evidence is lacking). Can disrupt spacecraft communications and damage electronic components unless adequate shielding is provided
Weak Nuclear	Short range/carried by *W* and *Z bosons* (mass of 80 Gev) and range of 10^{-18} . Strength is 10^{-6}	Involved in radioactive decay and *neutrino* interactions. Facilitates the deuterium fusion (in the Sun) and produces heavy nuclei
Gravitational	Long range, mediates the interactions between all matter in the universe. It is the most important factor in the understanding of the evolution of the universe (mass-energy relationship). Is thought to bemediated by a particle called *graviton*[b]. Strength is 6×10^{-39}	Has influenced evolution of life and affects human physiology on Earth (See Chap. 3 for further details)

[a]Adapted from *sciencepark.etacude.com/particle/**forces**.php* and www.windows2**universe**.org/sun/…**forces**/4**forces**.html
[b]Theoretical designation for a very small particle without mass and not detected yet

Box 2.1 Definitions: Planets and Minor Planets
In 2006, the International Astronomical Union (IAU) adopted the following criteria to satisfy the designation of a planet:

1. Orbits the Sun
2. Has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
3. Has cleared the neighborhood around its orbit.

A *dwarf planet* is a planetary-mass object that is neither a planet nor a natural satellite. The first five dwarf planets are:

1. *Ceres* (located in the asteroid belt)
2. *Eris*
3. *Haumea*
4. *Makemake*
5. *Pluto* (reclassified in 2013)

A *circumstellar habitable zone* is the region around a star, where planets can retain liquid water necessary to support life (similar to Earth).

Apollo 11 was the first Moon visit by astronauts, who left a commemorative plaque (Fig. 2.1) on July 20, 1969. The Apollo 17 Moon Landing mission ended on December 7, 1972. No other humans have ventured beyond the confines of low Earth orbit (LEO) since the 12 U.S. astronauts walked on the Moon.

The second half of the twentieth century witnessed the beginning of a robust space science research program, dominated by planetary robotic probes, orbiting satellites, planetary surface rovers, and space telescopes.

The prevailing understanding is that the *Big Bang,*[2] some 13.772 billion years (uncertainty of 0.4 %) ago, gave birth to the ever-expanding Universe [4]. Our *Solar System* was formed about 4.5 billion years ago (Box 2.2), and the planet *Earth* is approximately 3.8 billion years old.

The discovery of planets, orbiting other stars, rekindled the scientific and societal interest for the search of other habitable worlds. The first *exoplanet* was discovered in 1999. Since then the existence of some 1,900 exoplanets was confirmed. In 2015, using the *Spitzer* telescope, NASA scientists discovered the closest exoplanet at about 21 light years from Earth, and the *Keple*r mission confirmed the first near-Earth size planet in the "habitable zone" around a Sun-like star [5, 6]. This discovery, and the introduction of 11 other new small "habitable zone" candidate planets in early 2016, marked another milestone in the search for the presence of life beyond the confines of our Solar System.

Fig. 2.1 Apollo 11 commemorative plaque on the leg of the Lunar Module Lander (Courtesy of NASA)

[2]The Big Bang theory is not universally accepted. The presence of the cosmic background radiation and the red shift of the light of distant galaxies are considered potential evidence for the Universe expansion and the Big Bang theory [4].

Box 2.2 The Solar System

- The Sun
- Terrestrial Planets
- Asteroid Belt
- Gaseous Planets
- Dwarf Planets
- Kuiper Belt, Oort Cloud and Comets

Robotic explorers will continue to provide the necessary information to better characterize health risks and select the most rewarding places to visit. This knowledge will guide human travel beyond the LEO, which is still in a planning phase, and perhaps decades away. Identifying the existence of water (capable of sustaining indigenous life forms)—and other resources necessary to support, sustain, and expand human reach into the far corners of the Solar System—is important for the selection of "salubrious settlements" [7]. One of the primary scientific goals for such missions will be the search for extraterrestrial life [8], and open commercial opportunities.

The hazards and potential health risks of venturing beyond LEO are significant but not insurmountable. Similar to an occupational setting on Earth, space-related residual health risks will be managed through the implementation of policies and procedures, and in some instances even tolerated. Since 1999, NASA began addressing the bioethics of Solar System exploration with limited medical resources, acceptance of medical risks and informed decisions by astronauts and other stakeholders, including the public. Biocontainment and the use of planetary protection to minimize chances of back contamination, possibly from extraterrestrial microorganisms, remains a concern, requiring continued assessment and development of precautionary measures. Mindful concerns for an Earth encounter with an asteroid, with catastrophic consequences to terrestrial life, is used to advocate a deployment of a space warning and protection system [9].

Solar System exploration by humans is a complex and challenging but inevitable endeavor requiring additional technological and scientific breakthroughs. The United States and United Nations continue to address legal, political, and policy concerns guiding future space activities. Commercialization of space, such as tourism and exploitation of space resources, is in its infancy but demands further national and international guidance.

Most of the information summarized in this chapter is the result of intensive Earth-based astronomy observations and robotic planetary exploration. More detailed information is available on NASA Websites and scientific publications [10].

The Milky Way Galaxy and the Solar System

We reside in the Milky Way Galaxy, one of the more than 170 million populating the Universe. The term "galaxy" is derived from the Greek word *galaxias* meaning milky.[3] *Dwarf* galaxies contain thousands and *Giant* galaxies more than a trillion of stars, separated by space containing gas and dust used to generate more stars. It is hypothesized that the remainder of the universe is composed of *dark energy* (68 %) and *dark matter* (about 27 %). It is postulated that dark matter is a matrix or scaffolding holding the visible universe together, while the dark energy counterbalances the gravitational force, and is responsible for accelerating the expansion of the universe. Thus, the visible universe represents less than 5 % of the total matter. Stars and all matter within the galaxies are kept together by the week gravitational force, perhaps counterbalancing the dark energy expansion force.

Gamma-ray bursts are narrow beams of intense radiation believed to be formed by the collapsing supernovas forming *neutron stars* with potential damage to life on Earth. Cosmic and Solar radiation is of concern to space travelers beyond LEO and is further discussed in Chap. 7, Radiation Health and Protection.

Interstellar space is filled with 10^{-4}–10^{6} particles per cm^3 with 70 % hydrogen by mass. Most of the gases are from the explosions of dying stars. Some of the areas are denser and are known as clouds, or *diffuse nebulae*, also known as *stellar nurseries*. Stars are born in these nurseries, pulling together atomic and molecular gas (primarily hydrogen and helium) and tiny pieces of solid particles or dust (mainly carbon, silicon, and oxygen). Stars can be formed primarily through stellar clouds' collision and explosion, or by a phenomenon known as a *gravitational collapse*, which occurs when a massive cloud is unable to maintain a gravitational equilibrium. Overtime, increasing density and temperature result in deuterium reaction initiating the process of stars and planets formation [11].

The Solar System is located at the edge of the *Orion* arm, one of the four arms of the spiral *Milky Way Galaxy*, two-thirds of the distance from its center.[4] The arms of our galaxy are packed with stars and gaseous materials from which the stars are born. The diameter of our galaxy has been estimated at 100,000–120,000 light years (Box 2.3). The Milky Way Galaxy contains some 100–400 billion stars, rotating around a massive black hole (*Sagittarius A*). Over two-thirds of the known galaxies are barred spiral galaxies

[3]The glowing belt of stars across the night sky is as a disk-shaped structure as viewed from Earth, was called by the Romans *Via Lactea*, or milky way (as translated originally from the Greek).

[4]All cited numbers are approximations based on theoretical calculations. The diameter of the Milky Way Galaxy is estimated at 100,000 LY and one revolution of the Sun around the Galaxy is approximately 240 million years.

Box 2.3 Useful Measures (International System of Units or IS)

1. *Distance*
   (a) Astronomical unit (AU) defined as the mean distance of the Earth from the Sun or 1496 million kilometers.
   (b) Light Year (LY) is the distance the light travels in 1 Earth year (365¼ days) at the speed of 299,792,458 m/s. or 63,240 AU.
   (c) Parsec (parallax of 1 arc sec or pc) is equivalent to 3.2616 LY and measures the distance from an object in space as seen from the Earth at 1 AU from the Sun and *one arcsecond* (1/3600°).
   (d) Kiloparsec (kpsc) and Megaparsec (mpc) are used to express enormous distances of the Universe.

2. *Time*
   Since 1926 defined as the *Coordinated Universal Time* (UTC) is used as a time standard based on Earth's rotation (replaces the Greenwich Mean Time).

3. *Mass, Acceleration and Weight*
   (a) The *mass* (m) of an object is determined by the amount of the matter it contains and its strength of its mutual gravitational attraction force. The unit of mass is 1 kg.
   (b) *Gravity* is the universal and natural force responsible for physical objects to move toward each other. The Newton (N) is the unit force necessary to accelerate 1 kg of mass over 1 m per second squared. The Earth's gravity is 9.807 m/s producing the centrifugal acceleration.
   (c) *Weight* is the force that gravity exerts upon a body, and varies based on the physical location. *Newton's Law* describing the relationship between Mass, Force and Weight can be expressed as:

$$F = Mass \times Acceleration$$

Thus, the weight of an object on Earth is:
$W = M \times A$
and on the Moon it will be:
$W = M \times 1/6\ A$

whose central bar-shaped structures are suspected to be the "star nurseries" of the region. The gravitational and electromagnetic forces are aligned along the Milky Way Galaxy's four spiral arms [12], which contain relatively younger stars. The Solar System consist of the Sun and the objects rotating around it.

The Solar System is contained within a *heliosphere*, often characterized as a region where the solar wind pushes against the interstellar medium and the Sun's gravitational force is greater than that of other stars. The *heliopause* defines the boundary of this region and is 123 AU (AU) from the Sun (Fig. 2.2).

Voyager 1 was the first human made object to reach the interstellar space and transmit a composite photograph of the Sun and its planets (Fig. 2.3).

The Sun: Properties and Life Cycle

Life on Earth is sustained by the remarkably steady energy output of our Sun. It is a medium *yellow dwarf* [5] (G2V) star, with a spherical shape and a radius of 695,508 km (100 times bigger than the Earth). Almost 99.98 % of the Solar System mass is contained in the Sun. The Sun is covered by the visible *photosphere*—a "liquid-like" plasma layer made of neon. Sunspots are irregular cooler and temporary regions on the photosphere and correspond to higher concentrations of magnetic field flux, which inhibits convection. Sunspots are responsible for solar flares and hot gassy ejections from the Sun's corona [13], suspected to contribute to climate change on Earth. The photosphere encases the denser silicon plasma, layered over a calcium ferrite rocky surface. The *chromosphere* is a layer of hot gases that envelops the photosphere. The temperature of the chromosphere increases from 3,726.85 °C at the lower to 19,726.85 °C at the upper edge. The *corona,* the outer layer of the Sun's atmosphere, can reach temperatures in excess of 1,000,000 °C.

The Sun completes 1 revolution every 250 million years around the Milky Way Galaxy core (containing a giant black hole), moving at 20 km/s toward the *Lambda Herculis*,[6] and at 7 km/s out of the plane of the Milky Way, reaching its maximum height in 10 or 20 million years [14]. Approximately 25 % of the Sun's mass is located in its core. The Sun is composed of about 70 % hydrogen, 28 % helium, and about 2 % of heavier elements such as carbon, oxygen, and iron. Nuclear fusion in the core transforms hydrogen into helium and produces temperatures reaching 15,000,000 °C as compared to 5,500 °C at the surface. The Sun's matter exists in a plasma state and behaves as a fluid subject to different rotation speeds—at its poles 936 Earth days and its equator 925.4 days. The Sun's denser core rotates as a solid body. Similar behavior is observed in the gas planets.

[5] About 10 % of the stars in our galaxy are yellow dwarfs. The Sun is actually white but appears yellow in color due to the Earth's atmosphere *Rayleigh* scattering phenomenon.

[6] Also known as *Maasym*, is a star in the constellation Hercules.

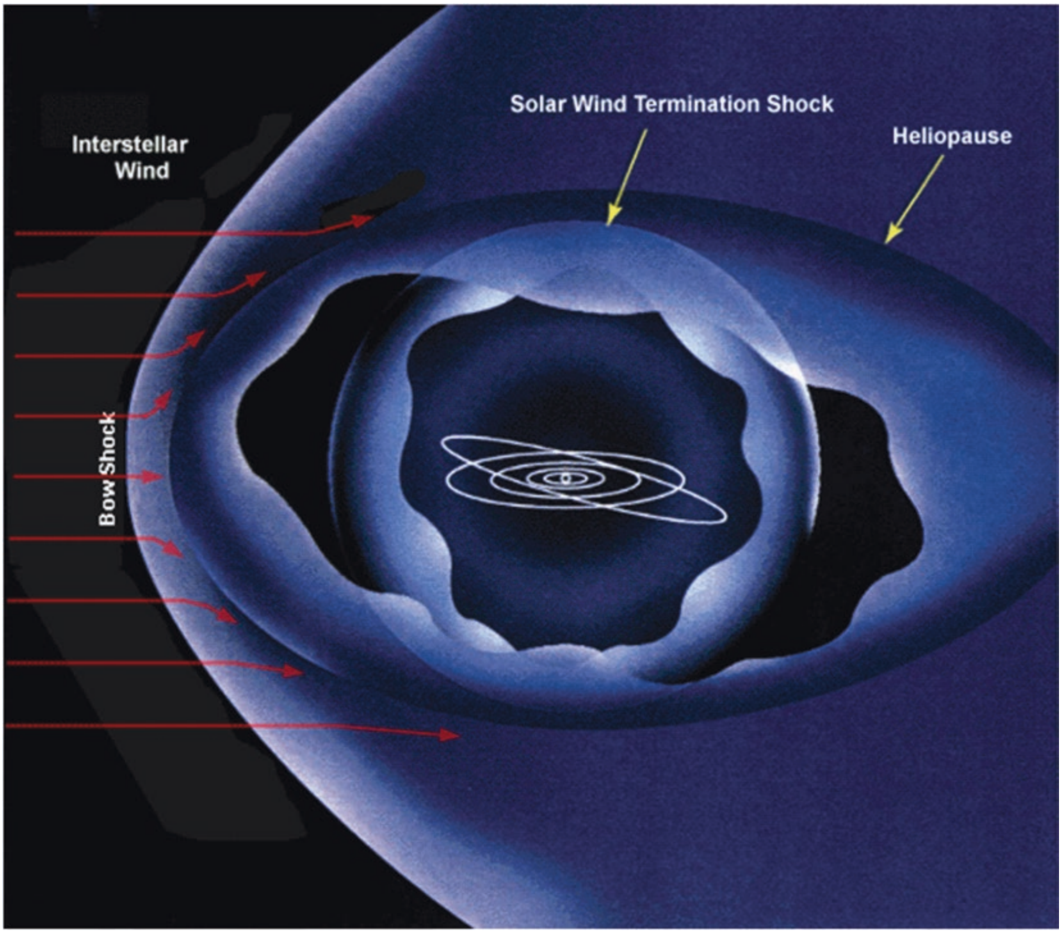

Fig. 2.2 A rendition of some of the main components of the heliosphere (Courtesy of NASA)

The Sun was formed 4.6 billion years ago, from a rotating giant cloud of gas and dust, and has already consumed half of its hydrogen,[7] with the remainder stores expected to last for another 5 billion years. After that, it will become a *red giant* star expanding and engulfing the Earth. In its final stages, the Sun will lose its outer layers, and the remaining core will collapse to become a white dwarf, and burn out its fuel sources.

The Sun periodically releases magnetic energy called *solar winds* and *storms*, visible as sunspots. Solar winds and storms form a stream of charged particles, traveling outward at approximately 450 km/s. The most severe documented solar storm to impact Earth, known as the *Carrington Event*, occurred in September 1859, producing Northern Lights visible as far south as Florida and "sparking" of telegraph wires that set fires in local telegraph offices. Solar winds and other space electromagnetic disturbances, are monitored by the U.S. government and a plan has been developed to protect both Earth and space-based vulnerable assets [15]. Solar winds represent a distinct health hazard to astronauts, especially on interplanetary missions. Monitoring the Sun's activity, observing the appearance of sunspots, space warning systems, shielding, and spacecraft "storm shelters" are part of a complex system of radiation safety tools used in human exploration missions. Figure 2.2 represents the Solar System as we know it.

[7]Hydrogen is transformed into helium through the fusion process.

Terrestrial Planets (Also Known as Telluric or Rocky Planets)

The four inner planets within the Solar System and inside the asteroid belt, are characterized by their smaller size, solid surface, and are located within the Asteroid Belt. Their distance from the Sun is considered to represent an envelope suitable to support life, as we know it on Earth, and is currently called the "circumstellar habitable zone" (CHZ) [16]. Astronomers and astrobiologists characterize the CHZ as the region around a star providing stable energy, supporting planets with suitable mass, a relatively stable rotation, a protective magnetic field (*magnetosphere*) from damaging radiation, liquid water, and an atmosphere.

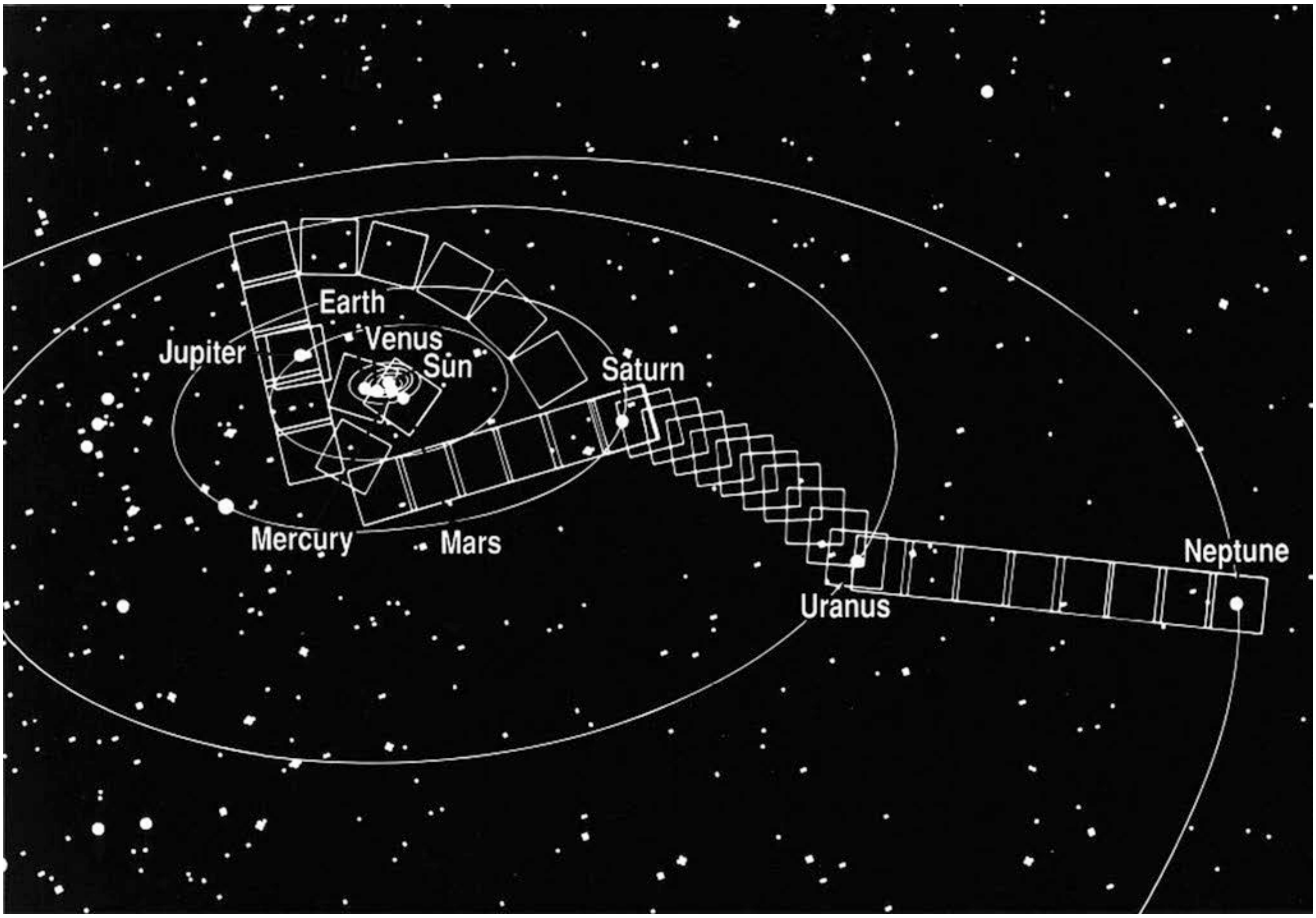

Fig. 2.3 The Sun and the planets of the solar system as photographed by *Voyager 1* (Courtesy of NASA)

Planetary Magnetospheres

Earth, Mercury, Jupiter, and Saturn produce an internal magnetism forming an envelope called a magnetosphere. These magnetic fields deflect solar winds' charged particles and form an elongated magnetotail. When the highly conducting plasma rearranges magnetic domains and transforms magnetic energy and thermal energy, it is referred to magnetic reconnection and contributes to the loss of particles. Smaller than Earth's, magnetotails are also detected on Venus and Mars [17].

Mercury

Mercury is 77.3 million km at its closest distance from the Earth (Box 2.4) [18]. Mercury has no satellite and is the closest planet to the Sun. Its distance from the Sun is 0.466 AU at its farthest and 0.307 AU at its closest. In appearance, the heavily cratered surface of Mercury seems most like the Earth's Moon (Fig. 2.4).

Almost 40 % of the planet's surface shows evidence of volcanic activity contributing to the crust formation, which is rich in iron- and titanium-bearing oxides [19]. The Earth-based images of the north and south poles of Mercury show highly reflective areas suggestive of an icy presence [20]. Mercury's weak magnetic field does not support a *Van Allen*-type radiation belt, unlike all other planets in the Solar System with internal magnetic fields. The bulk density of Mercury, however, is much higher than that of the Moon,

Box 2.4 *MESSENGER* Mission Discoveries (2004–2015)

Mercury (*source*: NASA.gov, *MESSENGER* Website http://messenger.jhuapl.edu/)

- Has a magnetic field suggesting a rotating molten core.
- Magnetic field is stronger in the northern hemisphere.
- Has a magnetotail [18].
- Had a volcanic history, and probably shrank as a result of long term cooling.
- Ice is present in the craters close to the poles, which do not see sunlight and are at −370 °C.
- Receives recurring meteor showers.

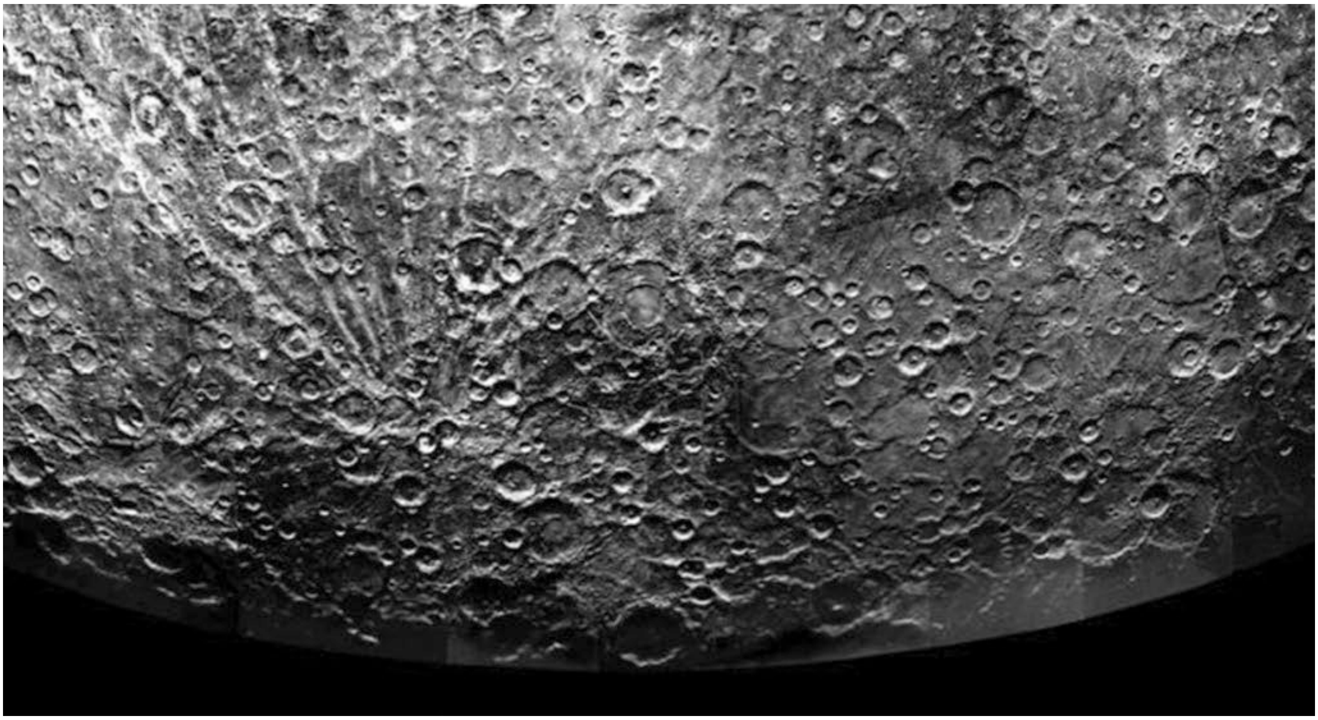

Fig. 2.4 Surface of Mercury from *MESSENGER* spacecraft (Courtesy of NASA)

suggesting a higher iron content, possibly concentrated as a molten iron-nickel in a sizeable core. Mercury's period of rotation on its axis is equivalent to 58.65 Earth days, and its period of revolution around the sun is 88 days, yielding a solar day on Mercury that is equal to 176 Earth days. During periods of illumination, the surface temperature rises as high as 690 °C when Mercury is closest to the Sun, while during the Mercurian night the uppermost surface cools rapidly to about 180 °C. The core is estimated to form 75 % of the planet, with a thin crust. The mission analysis of the spacecraft *MESSENGER* (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) indicated that Mercury's surface is a combination of high magnesium/silicon and low aluminum/silicon and calcium/silicon ratios [21].

Whether humans will ever journey to Mercury remains a matter for conjecture. Currently, no clear rationale exists for establishing a human presence on Mercury. Although in situ resources and the energy-rich environment of the near-Sun region (solar radiation flux at Mercury is approximately seven times that in the vicinity of Earth), together with modest amounts of polar ice might eventually attract interest of future prospectors using robotic systems.

Box 2.5 Winds on Venus
Wind speed on Venus tends to change with the time of the day and the altitude. The Venusian atmosphere extends up to 225 km. Within the sulfuric acid clouds (45 km and 66 km altitude) the wind speed ranges approximately from 210 to 370 km/h, and can reach 700 km/h in the middle cloud layers. At the surface, the pressure of the atmosphere is greater than 85 atm (>63,000 mmHg), which slows the wind speed to a few km/h but is still capable of moving sand and small rocks. Venus' rotation and winds are in a westerly direction, the same as its rotation. Seen from above, Venus rotates opposite to the other Solar System planets, which move counter-clockwise. Launched in 2010, the Japan Aerospace Exploration Agency's (JAXA) *Akatsuki* spacecraft malfunctioned, but was successfully inserted into the Venusian orbit in 2015 and began transmitting images in December 2015. This probe continues to study the Venusian climate.

Venus

Venus's average distance from the Sun is estimated at 0.722 AU, and is 70 million km. at its closest from Earth. Also, known as the "Earth's sister planet," it is the nearest planet to Earth and is more Earth-like in its properties than any other planet in the Solar System (Box 2.5). Venus is about 80 % of the Earth's size. The Venusian surface temperatures reach 480 °C, mostly due to volcanic activity and atmospheric greenhouse effect. The Venusian day is about 117 Earth's day-night cycle, and travels in 225 Earth days around the Sun. Thus, the Venusian sidereal day lasts longer than a Venusian year (243 versus 224.7 Earth days). Venus has a solid, cratered volcanic surface. The tallest peak is *Skadi Mons* rising at 6.4 km. NASA, Soviet/Russia, European Space Agency (ESA), and Japan Space Exploration Agency (JAXA) space agencies have provided a wealth of information on the planet's characteristics. Beginning in 1965, Soviet spacecrafts probed the atmosphere, landed cameras and experiments on the surface, and obtained spectacular radar images of the planet. Orbits that make use of Venus' gravity are important in conducting missions to other planets. The Soviet *VEGA* (Venus-Halley's Comet mission) used a Venus "swing-by" as part of its orbital mechanics,[8] as did the later *Phobos* mission to Mars. ESA's Venus Express and the NASA Magellan mission explored Venus' atmosphere composition and surface features [22].

Venus is obscured by clouds that contain sulfuric acid aerosols suspended in an atmosphere largely composed of carbon dioxide. Water vapor, nitrogen, and sulfur dioxide have been detected in the atmosphere. Although the atmosphere of Venus reflects 75 % of the incoming solar energy, the high carbon dioxide content traps nearly all the rest, bringing the temperature at ground level to approximately 500 °C. The rotation of Venus on its axis is somewhat slower than its travel around the Sun in a retrograde rotation (sunrise in the west rather than the east). Equatorial winds are strong at high altitudes (100 m/s), but measured wind velocities are slight at the surface (1 m/s). The temperature difference between day and night at the planet surface also seems to be slight. Lightning storms have been detected in the Venusian atmosphere and may contribute to the night glow observed with satellite instruments.

Venus has no intrinsic magnetic field to shield it from the solar wind. The *ionosphere*, formed by the interaction of solar ultraviolet radiation with the atmosphere, acts as an obstacle to the solar wind, and ends abruptly at an altitude of a few hundred kilometers. The induced magnetic field at this "ionopause" transmits solar wind pressure to the *ionosphere*, causing the *ionopause* to move in and out with the solar wind and day/night fluctuations. Recently, a smaller than the Earth's magnetotail was discovered on Venus [23].

Three classes of physiographic features on the Venusian surface were discovered with the Pioneer-Venus radar altimeter [24]. Ancient crust, representing about 65 % of the surface area, lies at intermediate elevations; relatively smooth lowland plains occupy another 25 %; and the rest are complex continental highlands. The plateaus and mountains are as high as those on Earth, but the lowlands are only one-fifth the maximum depth of the Earth's oceanic basins. Current scientific opinion is that volcanic activity was important in shaping the continental masses, but that plate tectonics have not shaped the present surface morphology. The rigid crust supports the continental masses, suggesting that the crust is thick, dry, or both. The Magellan mission produced an enormous map of Venus at a resolution of about 300 m. The surface. is still geologically active with evidence of recent volcanism. The surface is also dominated by compressional features "corona" suggestive of volcanos and tectonic "tessera" formations. Many intriguing features are unique to Venus [25]. Clearly, the surface of Venus has not evolved in the same way as that of the Earth and is the subject of additional studies.

Venus is not expected to represent a target for human missions because of its high surface pressure and temperature. However, "fly-bys" of human spacecraft are possible, because some trajectories from Earth to Mars use Venus' gravitational field to achieve the proper orbital characteristics. Long-lived floating stations could exist in the atmosphere; such balloons have been developed by the French for Soviet missions to Venus. Eventually, such floating facilities could become laboratories where initial experiments might investigate long-term modification of the atmosphere of Venus.

The Earth

The Earth, known as the *Pale Blue Dot,* orbits the Sun at the distance of 1 AU distance. By definition the Earth is located in the habitable zone for life to flourish. Carl Edward Sagan (1934–1996) is credited for arranging a picture shot of Earth by the *Voyager 1*, as the spacecraft was reaching the edge of the Solar System (Fig. 2.5) [26]. Extensive geologic observation, isotopic analyses of the elements and radioactive decay estimate the Earth's age at 4.543 billion years. Earth is the only rocky planet of the solar system to have abundent stores of water. The origin of the water on Earth continues to be debated. The favored hypothesis is that water was delivered by the impact of comets shortly after the Earth's formation [27, 28]. The United States Geological Survey (USGS) estimates that 71 % of the Earth's surface is covered by water, with the total stores at about 1386 million cubic kilometers.

Earth's water circulates throughout the surface and the mantle forming large stores [29]. On the surface, water is present in liquid and ice, and as vapor in the atmosphere.

Earth's atmosphere exhibits distinct vertical density, pressure, and temperature gradients. As altitude increases, the density of the gaseous medium that surrounds Earth decreases (Fig. 2.6). The upper boundary of Earth's atmosphere is defined as the area where collisions between air molecules become infrequent and immeasurable (about

[8] Also as is used to calculate launching navigation to and from Earth orbit or planetary missions.

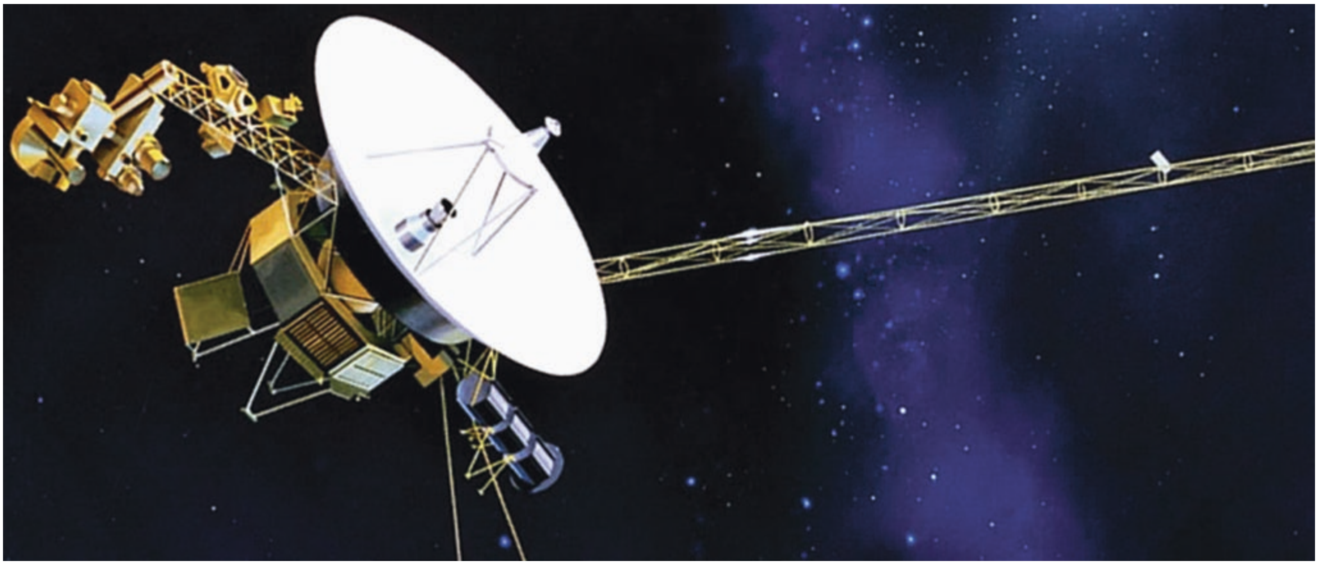

Fig. 2.5 *Voyager* spacecraft (Courtesy of NASA)

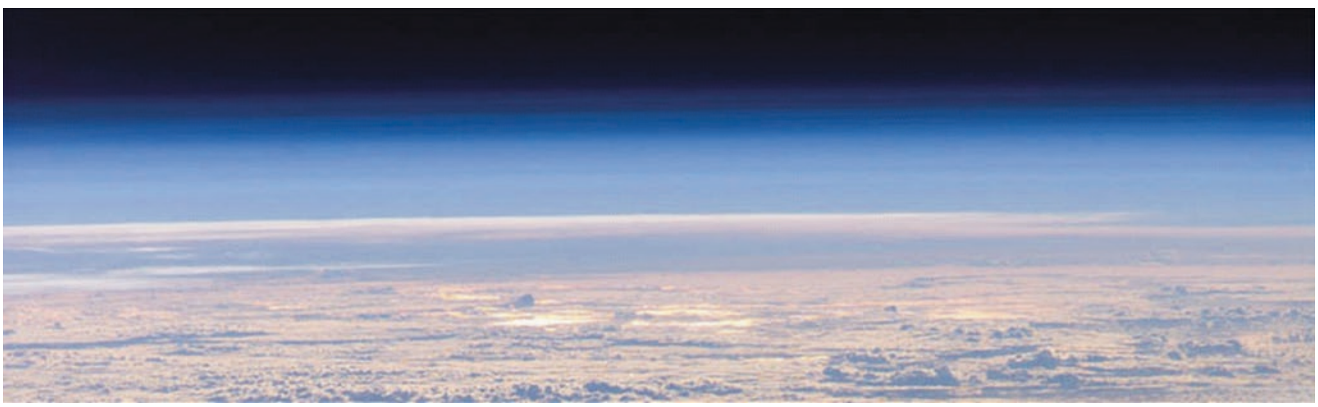

Fig. 2.6 Layers of the Earth's atmosphere as seen from the International Space Station (ISS) (Courtesy of NASA)

700 km above the surface). Beyond the exosphere, a zone of declining and free-moving air particles gradually transition into true space.

Transition to Low Earth Orbit

Atmosphere

Transition from Earth's atmosphere to free space includes two zones of particular interest for spacecraft designers (Box 2.6). The *von Karman* line, at approximately 80 km above Earth's surface, is the maximum altitude at which aircraft control surfaces are aerodynamically effective.

At higher altitudes, the orientation of space vehicles must be controlled by reaction jets (Box 2.7). The second area is the mechanical boundary between atmosphere and space, where air resistance becomes insignificant, approximately 200 km above the surface. Travel to LEO and beyond requires specially designed systems to protect humans against reduced atmospheric pressures, declining oxygen availability, and temperature changes (Table 2.2) [30–33]. An object traveling through the atmosphere will experience an *aerodynamic drag force*, which depends on the shape and velocity, and is counteracted by the lift force. Similar effects are

Box 2.6 Troposphere

1. Contains >75 % of the atmosphere's total mass
2. Changes with the space and time. Weather occurs in the troposphere. Extends 5–7 miles above the poles and 10 miles from the equator,
3. The temperature in the troposphere can reach −80 °C.

Box 2.7 Atmospheric gas composition, oxygen partial pressure and respiration.
With increasing altitude, the partial pressure of the atmospheric oxygen declines while its percentage remains consistent (# 20, 95 %). Decreasing alveolar oxygen pressure (PAO_2), is called *hypoxia*. This results in decreasing arterial oxygen pressure (paO_2), or *hypoxemia,* a clinical condition that leads to decreased tissue oxygenation and ultimately loss of consciousness (TUC), and, if not remediated, death.

A simplified formula used to calculate the PAO_2 is:
$(ATP\text{-}PP_{O2}) - 0.21 - (PP_{CO2}/RER)$
or
$(760\text{-}47) \times 0.21 - (40/0.8) = 99.78$ mmHg

Adjusted for venous shunting, it will yield an average of 99 mmHg partial pressure oxygen available as P_aO_2 (this value can change with age and body position).

Assumptions and explanations:

(a) 760 is the total atmospheric pressure at sea level (mmHg). The inspired air has negligible water vapor and CO_2,
(b) 47 is the partial pressure of the alveolar water vapor (mmHg), at body temperature of 37 °C
(c) 40 is the constant pressure (mmHg) of CO_2 in the alveoli and is equal to the CO_2 partial pressure of the arterial blood
(d) 0.8 represents the *Respiratory Exchange Ratio* (RER).
(e) Assume a small amount (≤1 mmHg) of venous shunting.
(f) $PaO_{2\ range}$ at sea level values are 90 and 99 mmHg depending on age and body posture.

observed during the reentry from space[9] [34]. Wiley Post (1888–1935) developed a high-altitude pressure suit [35], John Paul Stapp (1910–1999) who tested the limits of human tolerance to acceleration/deceleration forces, and Joseph Kittinger[10] (1928–) who performed a skydive from 19 km altitude to test survival equipment [36], contributed to the safety of human space flight by their pioneering research.

[9]For additional information on the subject matter please refer to the full description and equations at https://spaceflightsystems.grc.nasa.gov/education/**rocket**/rktaero.html [34].

[10]Advised Felix Baumgartner on his record-breaking altitude jump in 2012 in project Red Bull Stratos.

Gravitational Forces

The minimum escape velocity required to overcome Earth's gravitational force and reach LEO is about 40,270 km/h (25,020 mph). During this transition, astronauts may experience several changes in gravitational forces:

- During *ascent* through the atmosphere, spacecrafts and their occupants are subjected to vibration in addition to the Gx forces (antero-posterior or chest to back axis). Typically, the astronauts are launched in a supine position, with the feet higher than the head (supine-sitting). Lateral vibrations (≈12 Hz) can interfere with visual tasks and were of concern to the aeronautical engineers designing the now cancelled *Aries* 1. This problem has been resolved for the current Space Launch System (SLS) [37] through appropriate mass distribution and vehicle design.
  - *Orbital insertion*, characterized by free fall (microgravity) environment, is produced when gravitational force provides the centripetal force necessary to continuously change the tangential momentum into a circular or elliptical orbit. The latter takes place when the gravitational force vector is counterbalanced by the centrifugal force imparted to a spacecraft as it travels tangentially to the Earth's surface in LEO or similarly around the Sun on journeys within the Solar System.
  - *Acceleration* experienced by the rocket propulsion systems for navigational purposes in space and orbital attitude corrections. On occasion propulsion, or the lack of thereof, can produce acceleration forces that could affect crew performance [38].
  - *Travel through the Van Allen belts* represent a unique health hazards because of the trapped energetic particles. The inner and outer belts extend from an altitude of about 1000 to 60,000 km above the Earth's surface. The belts contain primarily electrons and protons, and vary in flux during geomagnetic storms. The inner belt contains high concentrations of electrons (up to 100 or more KeV) and protons with energies exceeding 100 MeV. Apollo astronauts reduced the radiation exposure by avoiding the inner belts and navigating through the thinner areas of the outer belt. The cumulative exposure ranged from 0.16 and 1.14 rads (1.6 and 11.4 mGY). Beyond the Van Allen belts the crews are exposed to Solar and cosmic radiations. All lunar activities did occur in between solar storms [39]. Additional information on the subject is provided in the Radiation Health Chap. 7.
  - *Deceleration* during reentry into the atmosphere of Earth or other Solar System bodies. Previous Earth and Moon launch and reentry forces experienced were well within the physiological-tolerance limits established for "healthy" individuals. Acceleration during launch

Table 2.2 Altitudes and physiological boundaries of Planet Earth. Adapted from [30–33]

Altitude[a] kilometers/miles (pressure in mmHg)	$PAO_2 - PaO_2$ (mmHg)[b]	Acute physiological effects	Countermeasure(s)	Policies and practices	Remarks and time of useful consciousness (TUC)[c] with moderate activity
0/0 at Sea level (760)	107–99[d]	None	None	None	None
4.16/2.55 (456.64)	36.02–36	Possible performance decrement	Supplemental O_2 delivered by a face mask.	– FAR Part 91.211 General Operating Flight Rules – NASA Standard 3001 — Volume B	Hypoxia symptoms can appear starting at 3 km 100 % O_2 is required after 30 min of exposure to the ambient air to prevent hypoxia. Without supplemental O_2 TUC is about 30+ min at 3.9 miles
13/8 (124.12)	Lung volume filled with CO_2 and H_2O	Hypoxia and cold exposure	Oxygen limit maximum altitude for sustained O_2 breathing through a pressure mask Requires warm clothing to prevent hypothermia	– FAR Part 91.211 General Operating Flight Rules – NASA Standard 3001 — Volume B	Loss of consciousness without 100 % continuous O_2 breathing (TUC 9–15 s) 8 km region is also known as the "**death zone**"
15/9 (90.5)	Lung volume filled with CO_2 and H_2O	Severe hypoxia and cold exposure	Pressure breathing with 100 % O_2 Partial or total pressure suit might be required Requires warm clothing to prevent cold injuries in prolonged exposures	– NASA Standard 3001 — Volume B	The upper limit of the *Tropopause*, where all the meteorological phenomena occurs. Its height varies with latitude (7.01 km at the poles and 19.81 km at the equator) and seasons. Over 75 % of the atmosphere mass, water vapor, and dust particles are in the troposphere
20/12 (40.85)	Lung volume filled with CO_2 and H_2O	Liquids in exposed tissues — boils	Physiological limit for sustaining life without a pressurized cabin or full body space suit (self-contained) to maintain atmosphere, temperature and pressure control	– NASA Standard 3001 — Volume B	The Armstrong line is defined as the altitude at which water boils at body temperature or between 18.9 and 19.35 km (~12 miles)
80/50 (0) Atmospheric pressure is 7.70×10^{-3}	Lung volume filled with CO_2 and H_2O	*Ebullism*, Incompatible with unprotected human life	Physiological limit for sustaining life without a pressurized cabin or full body space suit (self-contained)	– NASA Standard 3001 — Volume B	Also called v*on Karman* boundary. Aerodynamic control no longer effective TUC about 11 s (animal studies)
700/435 (0)	Lung volume filled with CO_2 and H_2O	"Space Vacuum" results in ebullism	Physiological limit for sustaining life without a pressurized cabin or full body space suit (self-contained)	– NASA Standard 3001 — Volume B	Collision limit between air molecules. Ambient pressure is 2.50×10^{-10} TUC less than 10 s (animal studies)

FAR US Federal Aviation Regulations

[a]Approximate numbers

[b]PAO_2 alveolar and PaO_2 arterial partial pressure of oxygen

[c]TUC is ½ of the values shown after rapid decompression. TUC is defined as the loss of functional ability to perform following exposures to reduced (or interrupted) oxygen supply during altitude ascent in an aerospace environment. The values are shown for moderate intensity physical activity as defined by the US Centers for Disease Prevention and Control (http://www.cdc.gov/nccdphp/dnpa/physical/pdf/PA_Intensity_table_2_1.pdf). The value of TUC is approximatively doubled when sitting quietly

[d]Sea level PaO_2 at 37 °C ranges from 98.2 to 100 mmHg

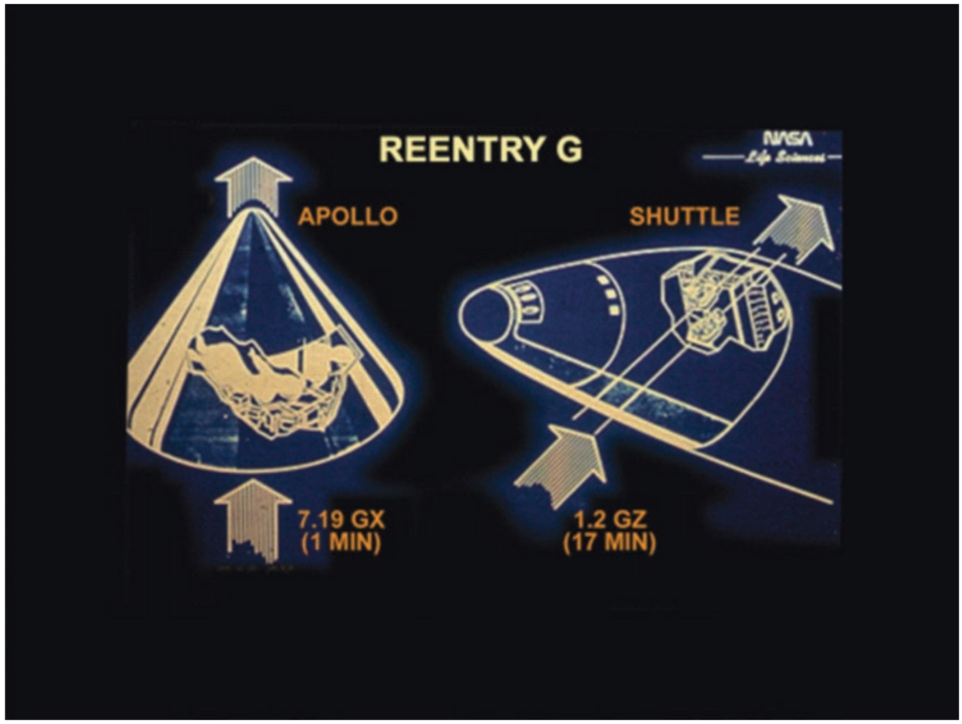

Fig. 2.7 Reentry acceleration forces experienced by Apollo type spacecrafts and the unique profile for the Space Shuttle as a sustained force for over 20 min time during landing with the crew in a sitting position and piloting the spacecraft (Courtesy of NASA)

of the Mercury-Atlas 6 flight, for example, reached 8 Gx in the chest to back direction for a brief period (Fig. 2.7). Forces exceeding 6 Gx were experienced during deceleration upon reentering the atmosphere. In contrast, the maximum forces experienced during launch of the first Space Shuttle mission (STS-1) were only +3.4 Gx. Moreover, acceleration forces during nominal Shuttle reentry were experienced in a different direction with respect to the body (Gz, head to foot), and reached a maximum of only +1.2 Gz (Fig. 2.7). These head-to-foot modest acceleration forces were sustained for much longer periods (17–20 min) than on earlier flights, and had significant physiological implications, particularly for the neurovestibular and cardiovascular systems, in pilots that have adapted to the space environment. In the foreseeable future returning crew members, using available Soyuz and the U.S. Orion vehicle, from long duration LEO space flight will be subjected only to Gx and not Gz forces.

Reentry into the Earth's Atmosphere and Landing

Spacecraft crews returning to Earth are at risk of injury and death during [40–42]:

- Nominal reentry into the atmosphere, which requires a proper angle of insertion to prevent destruction of the vehicle or bouncing back into the space. For example, the Space Shuttle, *gliding reentry*, traveling at 22 times the speed of sound, requires tilting its nose by 40°, using the thermal tiles to serve as a heat shield, and the hull as an air brake to slow down the descent rate. Friction with the air molecules raises the spacecraft surface to more than 15,000 °C, which ionizes the air and strips electrons from the atoms near the surface of the vehicles. This creates a zone of electromagnetic disturbance preventing radio communications for 17 or more minutes. Structural damages can lead to vehicle burn and destruction and crew death (see *Columbia* disaster in Chap. 1). At 3,962.9 km (13,000 ft) its speed begins to drop to 643 kmh (400 mph), its landing gear drops 11 s before touchdown, and unexpected wind gusts or crew performance decrements can cause crash, with damage to the vehicle and crew injury. Landing + Gx forces were 17 G for Apollo-type spacecrafts and were well tolerated by crews returning from long-duration space missions. Soyuz spacecraft, currently used as the International Space Station (ISS) crew return vehicle, use seats with shock absorbers and individually fitted liners to reduce the peak + Gx acceleration to less than 22 G. Further improvements under testing will reduce theses forces by 20–30 %. These force are sufficient to dislodged improperly stored items causing injuries during landing (Apollo 12). Water landings present the same hazards with added problems of drowning during crew egress.

Ballistic Reentry

Ballistic reentry is not a desired type of reentry. It is rarely used except during mission abort or a life-threatening event requiring immediate return. A best-case trajectory is selected using only drag for slowing down the spacecraft. In some instances slow rotation of the spacecraft might be required to reduce negative lift, which could affect crew performance. Surface temperatures can range from 1,926 to 3,315 °C.

Crew couches should be designed to absorb peak acceleration/deceleration forces not to exceed 17 G peak for a few seconds.

Ballistic type landings were experienced on Soyuz 1 and Soyuz TMA 1/ISS Expedition 6.

Spacecraft and EVA Suit Depressurization

Improperly sealed hatches, compromise of the spacecraft integrity, or collisions with other objects can cause loss of atmospheric pressure, bends (depending of the rate of pressure loss), and death. Such events did occur on:

- Soyuz 11/Salyut 1—In the descent module, a malfunctioning Soyuz hatch seal caused rapid depressurization and crew death on separation from the station and reentry.
- A small rod (palm bar) in a glove of an EV2 astronaut punctured the glove during a scheduled extravehicular activity (EVA) on STS 37. Differential pressure caused the flesh to seal the puncture hole, preventing depressurization.
- In 1997, the *Mir* crew was directed by the Moscow Mission Control Center (MCC) to practice a manual docking of a Progress resupply ship. The collision seriously damaged the orbital station, resulting in loss of power. The crew salvaged the station by rapidly isolating the damaged module.
- Intentional depressurization was accomplished during the historic EVA in 1965 by a Soviet cosmonaut, when a poorly designed space suit expanded, after exposure to the vacuum of space, preventing entry into the expandable airlock. According to a BBC interview, Cosmonaut General Alexei Leonov stated that he suffered bends and was exposed to thermal stresses [43] (Box 2.8 [44]).

Box 2.8 Decompression Sickness (DCS)

DCS is a condition arising from dissolved gases in the body coming out of solution as bubbles into the body's organs during depressurization. The clinical severity and symptoms are categorized as follows [44]:

- Type 1 (simple): involving the skin, musculoskeletal system, or lymphatic system, and
- Type 2 (serious): affecting major body organs, such as lungs and the nervous system.

Terms such as *bends* for joint or skeletal pain, *chokes* for respiratory difficulties, and *staggers* for neurological problems are commonly used to describe the symptoms. Joint pain is the most common complaint. DCS in space flight is a rarely reported event and has occurred twice.

DCS is of concern in spaceflight because of the large pressure gradient between the space suit and the cabin atmosphere. Preventive measures to DCS are discussed in Chap. 3. Re-pressurization and oxygen breathing are commonly used therapies.

Box 2.9 Meteoroides, Meteorites, and Comets

Meteor—a visual event related to the entry of a space object into the Earth's atmosphere at speeds in excess of 20 km/s.

Metetroid—a solid object moving in interplanetary space, of a size considerably smaller than an asteroid and considerably larger than an atom or molecule (between 10 m and 100 μm).

Meteorite—a meteroid reaching the Earth's surface.

Micrometeorids and space dust—describes very small particles less than 100 μm in size.

Comets are leftovers from the formation of the solar system, and composed of ice coated with dark organic material, frozen gases, rock and dust.

(Adapted from [45].)

Meteorites

Meteorites are remains of the disintegration and fragmentation of meteoroids and asteroids that orbit the sun, and pass through Earth orbital space at an average velocity of about 16 km/s (Box 2.9) [45]. Meteorites are primarily *chondrites* (rocky type), with 6 % formed as a rock and metal compound, or *stony-iron* meteorites. Modern classification of meteorites is complex [46]. Several carbonaceous chondrite meteorites contain organic carbon similar to terrestrial biomolecules, with some amino acids show a unique l-asymmetry [47].

Meteoroids larger than about 1 mm that collide with Earth's atmosphere leave trails that can be recorded with photography and/or radar from the ground. About 200 kg of meteoroid mass is expected to be within 2,000 km of Earth's surface at any one time. The largest fraction of this mass comprises meteoroids of diameters about 0.1 mm. A lesser fraction comprises meteoroids of diameters between 1 mm and 1 cm. However, this distribution of mass and velocity is sufficient to require shielding on some spacecraft.

Designing shielding can become complex when unique materials to fit the geometric properties of spacecrafts. Historically, shielding as light as thermal insulation blankets

Box 2.10 Crew Safety and Collision Risks
Three types of risks avoidance based upon the size of the object are identified

1. Ten centimeter and larger, require collision avoidance maneuvers. This size object can be identified through the surveillance network.
2. Less than 10 cm in size are usually too small to track or to shield against, and
3. Shields can be effective in withstanding impacts of particles smaller than 1 cm.

Debris avoidance maneuvers are planned when the probability of collision from a conjunction reaches limits set in the Space Shuttle and Space Station flight rules. If the probability of collision is greater than 1 in 100,000, a maneuver will be conducted if it will not result in significant impact to mission objectives. If it is greater than 1 in 10,000, a maneuver will be conducted unless it will result in additional risk to the crew.

The *Inter-Agency Space Debris Coordination Committee* (IADC), has been formed by different space agencies to coordinate to address orbital debris issues and to encourage operations in Earth orbit that limit the growth of orbital debris. The *Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space* (COPUOS). Both IADC and COPUOS have published orbital debris mitigation guidelines.

is usually sufficient to protect vulnerable areas such as wiring bundles and pressurized containers on small, unmanned spacecraft over their lifetimes, because only meteoroids smaller than 1 mm in diameter are likely to impact in these areas (Box 2.10). In contrast, shielding weighing several thousand kilograms may be required to protect habitation modules and fuel-storage tanks on space stations. The goal of such an effort would be to protect vulnerable areas consisting of hundreds of square meters from meteoroids of about 0.5 cm in diameter, with the likelihood of these areas being penetrated be less than 1 in 10 over the station's planned 30-year lifetime [48]. In general, the mass associated with a single sheet of aluminum shielding can be reduced up to fivefold by substituting aluminum "bumper" shields, which typically are only as thick as the meteoroid diameter to be protected against. Alternatively, some "multishock" shielding techniques involve about half the mass of an aluminum bumper.

Space Debris (Orbital and Geostationary)

Orbital debris are usually the remains of human-made objects with no useful purpose. According to NASA [49] more than 21,000 orbital debris larger than 10 cm are known to exist. The estimated population of particles between 1 and 10 cm in diameter is approximately 500,000 (Fig. 2.8). The number of particles smaller than 1 cm exceeds 100 million. These debris are present in LEO and also to a lesser degree in the geosynchronous region. Space debris travels at speeds up to 17,500 mph, fast enough for a relatively small piece of orbital debris to damage a satellite or a spacecraft. The rising population of space debris increases the potential danger to all space vehicles, but especially to the ISS, and other crewed spacecraft.

NASA and the U.S. Department of Defense (DOD) cooperate and share responsibilities for characterizing the satellite (including orbital debris) environment. DOD's Space Surveillance Network tracks discrete objects as small as 2 in. (5 cm) in diameter in low Earth orbit and about 1 yard (1 m) in geosynchronous orbits.

NASA has a set of long-standing guidelines that are used to assess whether the threat of such a close pass is sufficient to warrant evasive action or other precautions to ensure the safety of the crew. These guidelines propose a 2-dimensional rectangular region about a mile deep by 30 miles across by 30 miles long ($1.5 \times 50 \times 50$ km), with the space vehicle in the center. When predictions indicate that the debris will pass close enough for concern, and the quality of the tracking data is deemed sufficiently accurate, MCCs in Houston and Moscow work together to develop a prudent course of action. Allowing time to move the station trajectory (*debris avoidance maneuver*), is improved when these encounters are known well in advance. In preparation for collisions, crews isolate segments of the ISS by closing connecting hatches (to minimize the extent of depressurization) and move into the crew return vehicles (Soyuz). The crew is prepared to abandon the station, in case of severe structural or system damage, loss of vital system components. ISS collision avoidance maneuvers conducted between 2000 and 2014 are shown in Fig. 2.9.

Debris such as water, paint, fuels, other gases, etc. discharged from spacecraft may form a cloud surrounding the spacecraft and react with external surfaces triggered by solar ultraviolet and/or atomic oxygen reactions.

Geostationary orbit debris present a collision danger to satellites, and in the future can be a hazard for crews venturing to this region. The geostationary region is a valuable asset for governments and commercial service satellites (communications, Earth observations, etc.). Despite the availability of graveyard or disposal orbit for non-functioning, decommissioned spacecraft, upper launch vehicle stages and dangerous fragments are beginning to crowd the geostationary orbit. No formal international guidelines exist to address the disposal of discarded satellites, however, space agencies

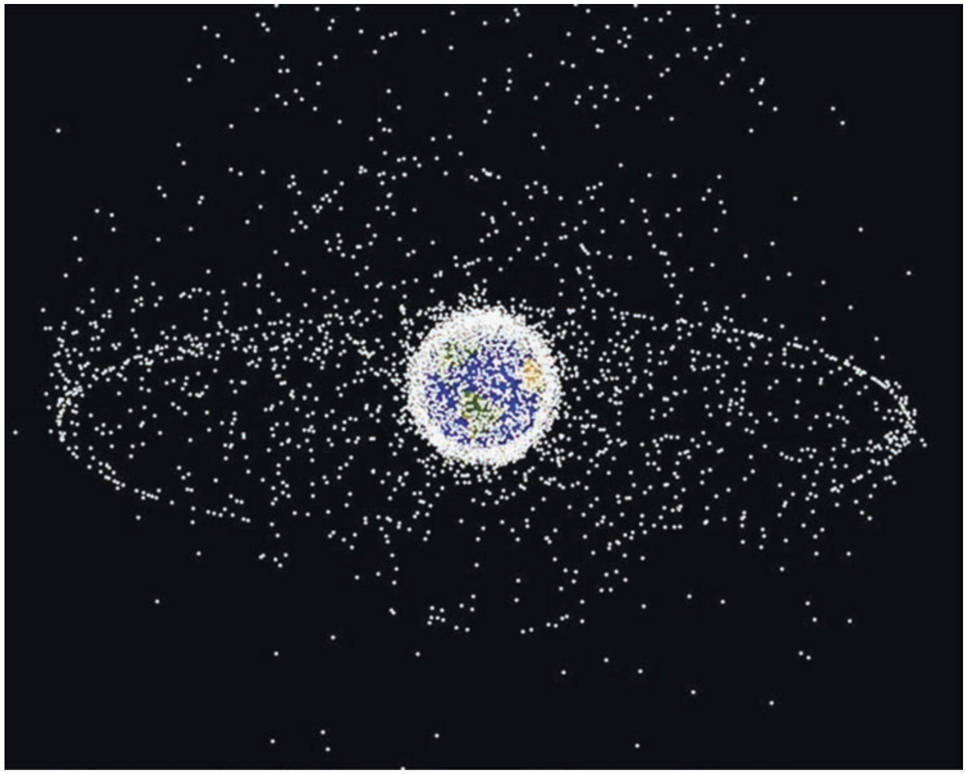

Fig. 2.8 A computer-made image of objects in Earth orbit currently being tracked. About 95 % of the objects in this illustration are non-functional debris. Most of the debris are the remains of human made objects (Courtesy NASA Orbital Debris office)

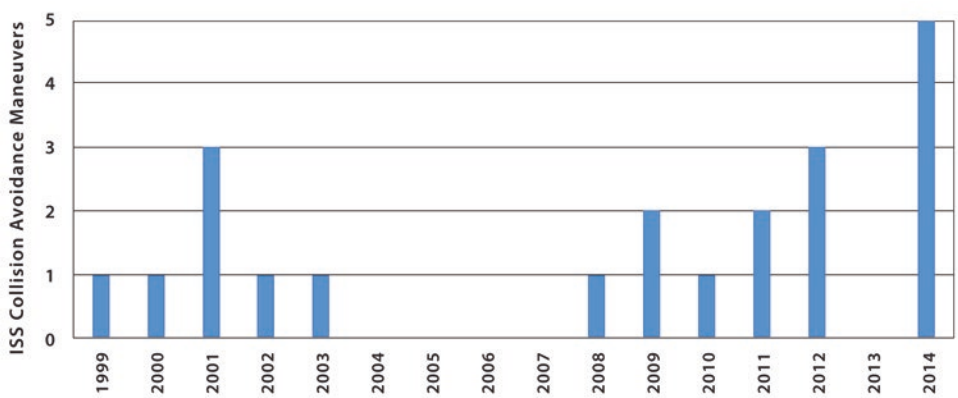

Fig. 2.9 Frequency of ISS collision avoidance maneuvers between 2000 and 2014 (Image credit: NASA)

have formed the Inter-Agency Space Debris Coordination Committee (IADC) to address orbital debris issues and to encourage operations in Earth orbit that limit the growth of orbital debris.

The Moon

The Moon is the only extraterrestrial body to have been explored by robotic probes and humans. Between 1969 and 1972, 6 Apollo missions transported 12 astronauts to the lunar surface, where they deployed instruments, explored the surface, and collected 380 kg of sample materials returned for study on Earth.

The prevailing, and contested, hypothesis is that the Moon is the product from a major collision between the Earth and another large neighborhood orbiting object [50] (Box 2.11 [51]).

The Moon's composition is like the Earth's mantle, consisting largely of the same elements, with similar isotopic ratios of important elements, such as oxygen (the ratio of $^{16}O/^{17}O/^{18}O$ are identical for the two bodies, whereas these ratios are different in all meteorites).

The young Moon apparently was in a molten state allowing the crust to be formed by the flotation of less dense silicates toward the surface. The volatile materials that may have been present initially were lost to space. Thus, the Moon has virtually no atmosphere, and the rocks at the surface are free of volatile compounds, such as water. Small and large impacts produced craters on the Moon's surface and created huge basins (the largest of these, *Mare Imbrium*, is about 1050 km in diameter) that were later filled by the volcanic rocks that form the dark *lunar maria*.

Box 2.11 Moon's influence on Earth and sustaining life

At present the Moon, is located 380,000 km from the Earth and is receding at 3.8 cm/year. This recession causes slowing of the Earth's spin. The Moon is responsible for the:

- Stabilizing of Earth's rotation axis.
- Length of the Earth's day.
- Diurnal tidal flows and heat transport from the equators to the poles and climate oscillations, resulting in migrations and species diversification.

Source: [51]

No life forms were discovered in the lunar samples, despite intensive examination in a specially constructed *Lunar Receiving Laboratory* that served as a quarantine facility for lunar samples from the first three Apollo missions. The contrast between the surface colors of Earth and moon is strikingly displayed in Fig. 2.10. When it was determined that lunar materials posed no threat to terrestrial life forms, the strict medical crew and samples quarantine was discontinued for the remaining missions. Highly sensitive analyses for organic compounds, such as amino acids, were conducted on special samples that had been protected from any possibility of terrestrial contamination. Small amounts of carbon, nitrogen, and hydrogen compounds formed from nuclei implanted by the solar wind were found in all lunar surface soil samples, but no evidence of indigenous complex organic compounds have been identified so far [52]. Even organic compounds known to survive in some meteorites were absent from the lunar soil samples.

The lunar surface has been bombarded over time by micrometeoroids, as well as cosmic rays. Most of the surface is covered by several meters of powdered soil. It is hypothesized that the lunar dust grains (*regolith*) and the solar winds

Fig. 2.10 NASA's Lunar Reconnaissance Orbiter (LRO) view of Earth from the spacecraft's vantage point in orbit around the Moon (courtesy of NASA)

results in hydrogen absorption and formation of the surface traces of water [53]. Lunar dust and its health risks to humans is the subject of continuous investigations, using animal models [54, 55]. No ill effects from the lunar dust except for skin and respiratory irritation were reported by the 12 astronauts who walked on the Moon. However, the lunar dust is found to be highly abrasive and electrostatically charged (probably due to continuous radiation exposure), causing vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, and seal failures [56]. Particles cling to surfaces and are hard to be dusted off or vacuumed and can remain suspended in the atmosphere. Future lunar exploration systems should address these dust properties to prevent mechanical failures, structural damage, and health risk.

Like on Mars, lava tube openings were detected on the Moon. These cavern-type structures, with stable temperatures and perhaps containing ice water, can offer human visitors protection from incoming meteoroids and cosmic and solar radiation. For extended stays, habitats must be constructed with shielding equivalent to about 2 m of lunar soil, with adequate shelters to protect against solar particle events (flares).

Possibilities for lunar colonies have been periodically studied by NASA for more than five decades. A NASA Study Group [57] concluded, “Space colonization appears to offer the promise of near limitless opportunities for human expansion, yielding new resources and enhancing human wealth. The benefits and significance of a permanent human presence on the Moon, including the ability to assemble and launch planetary missions, because of the low escape velocity, are subject of continuous assessments” [58, 59].

Among the attractions of a lunar base, aside from scientific importance, is access to indigenous resources and a low gravity pull, making solar system missions more efficient, by allowing sizable payloads. The highest effectiveness is gained if all propellants can be manufactured from lunar materials (for example, cryogenic hydrogen and oxygen or aluminum and oxygen), or if alternative means of propulsion that require no expendable propellants, such as electromagnetic launchers, can be developed [60]. Under these conditions, lunar materials could be used in space for 5 % of the energy and possibly the cost of equivalent delivery from Earth. Thus, provision of bulk materials, such as liquid oxygen for use in rocket systems, or materials for space construction or shielding, could become a major activity of a lunar settlement in addition to the scientific rationale [61, 62]. Recent findings of ice presence should be of great logistic help. The volatile elements hydrogen, carbon, and nitrogen are rather scarce on the Moon, contained primarily in the soil; however, they should be extracted easily by heat, and the total lunar inventory is substantial. Mining for helium-3 (He-3) has been proposed as a justification for commercial development [63]. He-3, discovered in a soil sample from *Camelot* crater returned to Earth by the *Apollo* 17 crew, can be a source for nuclear fusion and energy production, but its existence on the Moon in large enough quantities and mining difficulties has been challenged.

Because the Moon has no magnetic field, particulate radiation strikes the surface with unabated intensity. Settlers also must adapt to days and nights equivalent to 14 Earth days, and surface temperatures that range from as low as −178 °C in the dark to 110 °C in direct sunlight. These restrictions, and the one-sixth gravity of the lunar surface, will control the architecture of lunar development. Clever engineering approaches will be necessary to develop self-sufficient, safe and comfortable habitats.

Box 2.12 Solar Winds and Mars Climate
NASA’s Mars Atmosphere and Volatile Evolution (*MAVEN*) robotic spacecraft findings suggests that the Sun’s winds washes gas from the Mars atmosphere into space, at about 100 g/s. This process transformed the early warm and wet environment into the current cold and arid planet. This erosion is more pronounced during solar storms [64]. Magnetic reconnection has been reported in the Mars magnetotail [65].

Mars

The average Mars distance from the Sun is 1.52 AU (Box 2.12 [64, 65]), and 55 million km at its nearest approach to the Earth, which is a rare occurrence. The “launch window” for visits to Mars, occurs about every 2 years and 2 months, during its Earth *opposition.*[11] Throughout the past two centuries, “the red planet” has been a source of inspiration for astronomers, science fiction writers, and, more recently, politicians. Space age explorations—particularly Mariner 4, Mariner 9, Viking, international Mars Explorers and rovers—have shown Mars to be a dry planet with an intriguing geological past. Evidence from Mars missions suggest that the planet may have been much warmer and wetter in the past. Despite the finding of polar ice, no life forms have been detected yet. Huge volcano sites, one as large as the state of New Mexico, are among the Mars surface’s youngest features. Great chasms in the crust, within which Earth’s Grand Canyon would practically disappear, testify to internal forces that

[11] The launch window is a time period of opportunity to launch a spacecraft to Mars (or other planets and destinations). Usually planetary missions are launched several months or weeks before the opposition occurrence.

wrenched the planet's crust in ancient times. In addition, many canyons and other sculpted features suggest past fluvial erosion, which raises questions about past climatic conditions, as the current atmospheric pressure is so low that liquid water would not be stable at the surface. Other features suggest widespread subsurface permafrost poleward of 30° latitudes. The polar caps consist of frozen carbon dioxide and water ice, and can be observed (from Earth) to migrate with the Martian seasons.

Mars, like Earth, has produced basaltic volcanoes, suggesting that volcanism is a general property of planets. Deconvolution of compositional data suggests that the younger Mars produced volcanic iron-rich basalts, similar to those found among the *Shergottite* meteorites. This finding reinforces the hypothesis that the Shergottite meteorites, discovered in Antarctica, are actually Martian rocks expelled by large impacts [66].

The Martian atmosphere, in contrast to that of Venus, is extremely thin, with surface pressures, less than 15 of the sea-level atmospheric pressure on Earth. Like Venus, the atmosphere is composed principally of carbon dioxide, with significant amounts of nitrogen, argon, neon, oxygen, and small amounts of water vapor. Mars rotates once on its axis in a little over 1 Earth day, and the atmospheric circulation bears some resemblance to that of Earth. Viking photographed small clouds near the peaks of the highest volcanoes and surface frosts in the vicinity of the landers. Gigantic dust storms have been known to exist for some time, and the Mariner 9 spacecraft, which orbited Mars in late 1971, photographed a planet-wide dust storm that persisted for 2 months before the atmosphere cleared. Fine regolith particles found on the surface are lifted by the thin Martian atmosphere and are transported around the planet.

Viking, following on robotic probes and Martian rovers, failed to detect presence of life. Instead, they demonstrated that the Martian soil contains highly reactive agents, and probably did oxidize all organic materials. This hypothesis and laboratory experiments together with the unexpected findings of perchlorates—reactive chemicals first detected in arctic Martian soil by NASA's Phoenix lander in May 2008 and Mars rovers—suggest that the dust particles may have surfaces more highly reactive and could present a distinct risk for lung toxicity [67].

Mars has two small satellites, *Phobos* and *Deimos*, which might be captured asteroids. They seem to be of rather low density, and their reflectance properties suggest that they consist of materials like those in the carbonaceous meteorites. Phobos and Deimos are covered with a layer of fine-grained *regolith.*

Mars remains an attractive target for human exploration and the search for past and present life. Although distant, the planet contains the fundamental materials—water, oxygen, nitrogen, carbon—that, with appropriate controlled environmental facilities, could sustain life. Because the thin atmosphere is insufficient to filter out high-energy cosmic radiation, long-term habitation probably would be largely underground. However, surface and immediate subsurface temperatures are moderate, and daytime surface activities should be sustainable. Although the solar energy flux is about one-fourth than at Earth's surface, it may be adequate to support a human outpost. Studies have concluded that human missions will be feasible in the twenty-first century; however, they will present significant operational challenges, primarily because of the 2.5–3 years required for a round trip mission. Development of the indigenous resources of Mars and its satellites, Phobos and Deimos, could hasten the establishment of a permanent human outpost and an increase in Earth-Mars trips in the twenty-first century. A *Sabatier reaction* (similar to the ISS life support[12]), using crew respiration by-products and Martian atmospheric constituents, has been proposed as chemical regenerative life support and propulsion fuel to reduce exploration costs [68].

Box 2.13 The closest to Earth and smallest dwarf planet

The dwarf planet Ceres is 2992.1 km equatorial circumference and orbits the Sun at a distance of 414 million kilometers, 2.77 AU. One day is about 9 Earth hours and the length of a year is 4.6 Earth years. Ceres has a rocky core and an icy mantle with possible subsurface ocean. The planet surface is thought to be a mixture of ice and minerals in carbonates and clay. Two high-albedo features in craters, photographed by the Dawn mission, are thought to represent the vestiges of cryovolcanism and contain magnesium sulfate (E.B. 2016) (Fig. 2.11). The presence of an atmosphere is still debated and in 2014, ESA scientists detected water vapor plumes emanating from Ceres.

Asteroid Belt

The Earth is bombarded by asteroids originating in the asteroid belt between Mars and Jupiter. This belt comprises irregularly shaped small bodies, also known as minor planets. Close to 50 % of the mass of these objects is believed to be contained in *Ceres* (Box 2.13, Fig. 2.11), *Vesta, Pallas*, and *Hygiea*, the four largest bodies of the belt. They are thought to be left over from the early stages of solar system formation. Some asteroids, probably as a result of collisions, were

[12] $2H_2O \rightarrow O_2 + 2\ H_2 \rightarrow CO_2 + 4\ H_2 \rightarrow 2H_2O + CH_4$ (can be used as a propellant but currently discarded).

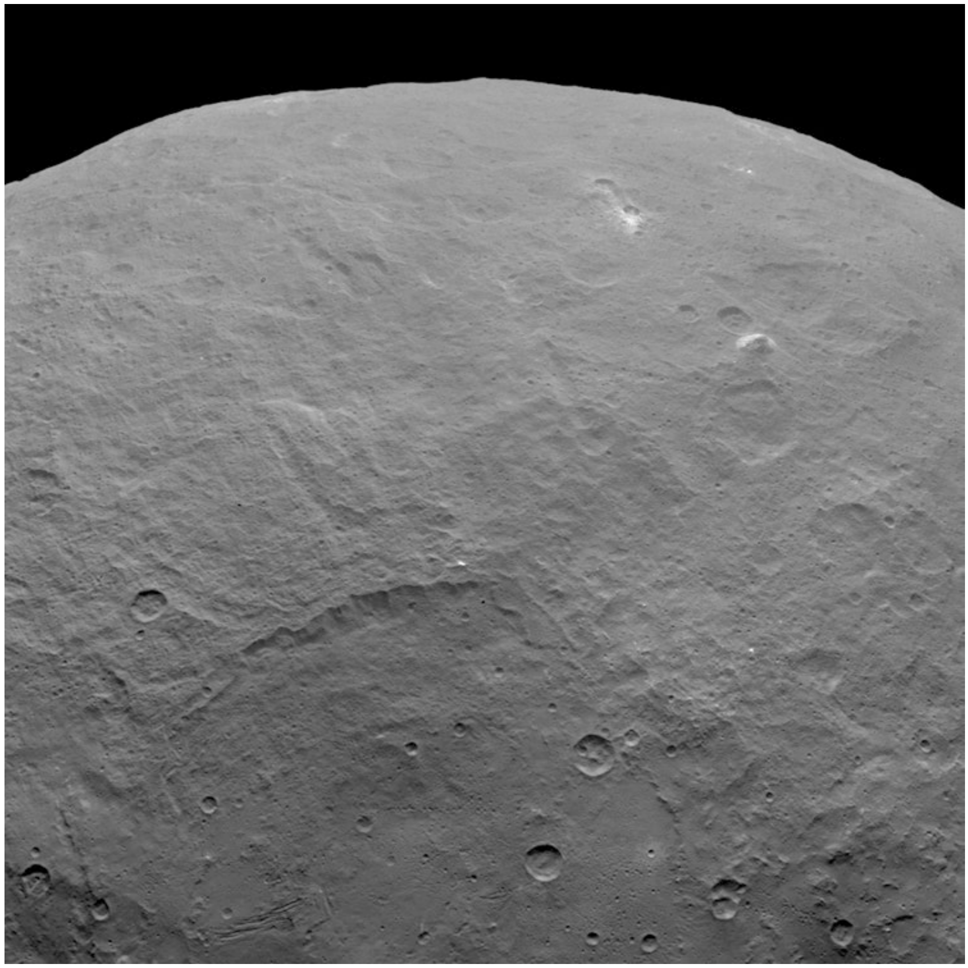

Fig. 2.11 Image of a cluster of bright spots on dwarf planet Ceres, taken by NASA's Dawn spacecraft on June 9, 2015. Credits: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

propelled into orbits from the Mars-Jupiter vicinity and migrated to the inner solar system region.

"Earth-approaching" asteroids have been objects of systematic observation since late 1976 [69]. Meteors present a significant threat to populations on Earth. They are claimed as the cause of periodic mass extinctions. Large meteors—such as the one that exploded near the city of Chelyabinsk, Russia on February 15, 2013—are rare, occurring every few decades. But as the Earth is more than 70 % water, many meteors of this size may strike the planet undetected.

The U.S. House of Representatives' bill, H.R. 1022, *George E. Brown, Jr. Near-Earth Object Survey Act,* was rolled into S.1281, the NASA Authorization Act of 2005, passed by the U.S. Congress on December 22, 2005 and signed by the President. The act directs NASA to establish a mechanism for "detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth." Two approaches under considerations are destruction of the threat with a nuclear device, and/or redirecting its trajectory with kinetic interceptors.

Some asteroids may be relatively easy to reach by humans in spacecraft. Asteroids contain large quantities of carbon molecules as well as the more usual rocks and metals. The study of meteorites suggests that metals, silicates, and hydrous substances may be accessible sources for developing a privately funded commercial industry [70]. NASA has been planning a robotic mission to visit a large near-Earth asteroid, collect a multi-ton boulder from its surface, and redirect it into a stable orbit around the Moon, where, astronauts could explore it and return with samples sometime between 2020 and 2030.

Gaseous Planets (Also Known as Gas Giants, Jovian or Outer Planets)

There are two giant gaseous planets, Jupiter and Saturn, and two others known as ice giants, Uranus and Neptune [71]. NASA robotic missions have visited and characterized these giants and their moons of the outer solar system. The presence of water, especially in their moons, has rekindled interest in their origin and evolution. Current propulsion life support technology places these solar system objects beyond the crewed exploration reaches.

Jupiter

Jupiter, the largest planet in the solar system, lies beyond the asteroid belt, about 7.78 × 108 km and 5.2 AU from the Sun. Jupiter has a mass 318 times and a density only one-fourth that of Earth. This gaseous giant has a miniature planetary system consisting of three thin rings and 67 moons (regular and irregular satellites) (Box 2.14). Scientists believe that if Jupiter were larger and generated higher temperatures leading to nuclear fusion, our solar system would be a double star system. It has been suggested that Jupiter's mass and gravity deflect some of the long-period comets, thus protecting life on Earth.

> **Box 2.14 Jupiter's rings and moons**
> Outer rings are called the *gossamer* rings and the thick inner ring is called the *halo*.
> Of the 50 confirmed moons, Ganymede and Io are considered potential human way station sites for future solar exploration.

The planet itself consists of condensed matter present in that region of space at the time of origin of the solar system, mostly hydrogen and helium. Debate continues on the presence of a significant core of rocks and ice [72] versus no existing core [73]. Because the planet radiates more heat than it receives from the Sun, it must have an internal heat source (probably converted gravitational energy) and elevated temperatures (with pressures so extreme that hydrogen may exist in a metallic state in the deep interior).

The atmosphere of Jupiter exhibits a complex motion due to thermal convection and planetary rotation. The dominant atmospheric features are banded belts and zones, the *Great Red Spot* and white ovals [73], exhibit anticyclonic, counterclockwise motion. The white oval features are quite fleeting; others, such as the *Great Red Spot*, have remained relatively unchanged for centuries. Both represent gigantic atmospheric storms. Materials within the Great Red Spot are observed to rotate once every 6 days (Fig. 2.12). The intensity of atmospheric turbulence is attended by substantial discharges of lightning.

Fig. 2.12 Jupiter's Great Red Spot and a white oval, taken by Voyager 2 from a distance of 6 million km on July 3, 1979 (Courtesy NASA/JSFC Voyager 2, P-21742)

The planet's magnetic field is the Jovian equivalent of Earth's Van Allen radiation belts, but more intense. The trapped charged particles in the magnetosphere, between 4 million and 8 million kilometers from the planet, create an intense radiation environment that poses a serious hazard to automated spacecraft and makes human exploration unlikely. The Jovian equivalent of solar flares also exist, and streams of hot plasma ejected from the magnetosphere have been detected both within and outside the magnetosphere.

Jupiter has at least 67 moons. Four of the largest satellites—*Io, Europa, Ganymede,* and *Callisto*—are considered unique "planets" in their own right. Io exhibits intensely active volcanism, with spectacular eruptions of sulfur-rich volatile compounds. This volcanism is considered to be caused by Jupiter's gravitational forces, exerted on the satellite, creating internal heat. Io's atmosphere is 90 % sulfur and the surface is probably rocky material and sulfur. Its core contains heavier metal elements such as iron, possibly responsible for its magnetosphere. Europa has an icy crust crisscrossed by stripes and bands that reflect a history of expansion and filling of cracks. Europa consists of approximately 20 % water, some of which may be in the form of a planet-wide ocean underlying the icy crust. Ganymede, the largest of the moons, apparently retains evidence of a primordial crust, which like Earth's moon retains a record of an intense impact history and is protected by two magnetic shields. Callisto is about the size of Mercury and is covered with impact craters. Except for Io, which has a thin "atmosphere" rich in sodium and sulfur, none of the Jovian satellites has a significant atmosphere.

Human missions to the Jupiter system are implausible at the current stage of space technology. Intense radiation, as well as distance from the Earth, create an environment inhospitable to human life. Nevertheless, a person able to observe Jupiter and its satellites from a vantage point near the planet would have an incomparable opportunity to contribute to the understanding of the Jovian system. In addition, the satellites, and possibly Jupiter itself, eventually may be tapped for their resources. An essentially unlimited supply of He-3 was detected in the Jovian atmosphere [74]. This isotope could be the fuel of choice for nuclear fusion reactors in the next century, but has not been considered due to its absence on Earth. Voyager Galileo, Ulysses and Cassini spacecrafts provided a wealth of information on the planet, its moons, and exploration resources such as water (see Table 2.3) [71, 75–87]. Io and Europa are considered candidates for extraterrestrial life and potential sites for future human settlements [88].

Saturn

Saturn is a large gaseous planet with seven rings, extending as far as 282,000 km, orbiting the sun at 9.5 AU (about 1.4 billion kilometers). Robotic missions to the planet survived the passage through its rings (chunks of rock and ice) to provide a wealth of information on the planet and its moons. Saturn's day is 10.7 h, and it orbits the Sun in 29 Earth years.

Saturn is composed largely of liquid molecular hydrogen and helium, under which is believed to be a region of liquid metallic hydrogen, with a solid rocky core constituting 25 % of the planet mass [72]. Saturn's total mass is 95 times that of Earth. Like Jupiter, Saturn apparently converts internal gravitational energy to heat, which flows toward the surface. Above the liquid surface, an atmosphere similar to that of Jupiter is present, containing dark belts, white-banded zones, and circulating storm regions. A stable red spot, similar to Jupiter's, is believed to be a manifestation of atmospheric convection. It measures about 11,250 km in length [89]. Maximum wind speeds at Saturn's equator can reach 1,600 km/h. Auroral emissions have been observed near the poles, but no lightning has been detected. Clouds in the northern hemisphere exhibit a hexagonal pattern, possibly a slow rotating storm, 2,000 km wide and 100 km deep, supported by winds. This vortex was studied by Cassini spacecraft using different wave length imaging in 2012. Scientists are still modeling the process to better understand the processes involved in its origin [90].

The rings of Saturn look like "dirty snowballs" [89], with particle sizes ranging from microns to meters. The well-known A, B, and C rings consist of hundreds of ringlets, some of which are elliptical in shape. The F ring is more complex, and may consist of three interwoven rings bounded by two "shepherding" satellites. "Spokes" of the B ring are probably formed from fine electrically charged particles above the ring, perhaps caused by lightning occurring in the ring. Saturn's rings exhibit unusual ripples, possibly reflecting the planet's inner processes [91].

More than 25 small satellites have been observed within the ring system [92]. The larger Saturn satellites show evidence of many craters. Saturn has 53 known moons, and nine more awaiting confirmation. With the exception of Titan, all of Saturn's moons are covered with water-ice [93].

Titan has a measurable atmosphere, consisting largely of nitrogen, with lesser amounts of methane, ethane, acetylene, ethylene, and hydrogen cyanide. The atmosphere is three times as dense and ten times as deep as that of Earth's. The atmosphere down to the planet's surface is quite cold, with a near surface temperature of −182 °C. The surface, which is not visible through the atmosphere, may be liquid methane or liquid nitrogen. *Cryovolcanism* and geysers of icy water, ammonia and methane have been detected (Box 2.15) [94–98].

Saturn remains a major scientific target for future explorations. Many interesting questions persist about the properties of its atmosphere, core, and rings. Titan represents a unique satellite with potential internal evolution similar to that of the terrestrial planets.

Table 2.3 Water and other useful exploration resources in select objects of the Solar System

Objects	Liquid water	Ice	Water vapor	Other resources (approximate values)	Comments
Mercury	Not detected	Traces in the polar craters, of possible recent origin discovered by the *MESSENGER* spacecraft	None	Basaltic minerals with 42 % O_2 Iron 5.4 g/cm^3 and Sulfur about 2.3 %	Possible source of ice from cometary impacts
Venus	None	None	0.002 % in the atmosphere	Rich in minerals	• Atmosphere contains CO_2, responsible for the greenhouse effect and N_2 • Mean surface temperature in excess of 461.85 °C. Does not support liquid form of water. Solar winds probably responsible for scattering O_2 and H contained in the Venusian atmosphere
Earth	71 % of the surface	10 % of the surface	4 % in the atmosphere	Contains both natural and human made resources	USGS estimates that 96.5 % of all Earth's water is contained in the oceans (salt water)
Mars	Possibly in warm underground areas and under the poles. MRO provided strong evidence of periodic surface flow of water	North Pole cap, ice-crystal clouds and possibly in the permafrost underground	Traces	Iron and nickel core surrounded by a crust of volcanic basalt rock, mostly silicon, oxygen, iron, magnesium, aluminum, calcium, and potassium [75] Phyllosilicates [76] Sulfates [77] Hydrated minerals [78]	Perchlorate salts detected at *Gale* crater (equatorial regions) suggests the presence of liquid brine [79]
Asteroid belt and small planets	Ceres and other small objects suspected to have liquid water	Contains significant stores of ice. Ceres has a mantle of ice over a slushy ocean	Water vapor on the dwarf planet Ceres detected in in 2014	Rich in ore and rock. Based on spectral analysis they are divided into: 1. C-type primarily carbonaceous 2. S-type, which are silicon-based or stony	Potential for commercial prospecting [80]
Calisto (moon of Jupiter)	Subsurface salty ocean with small amounts of ammonia	On the surface	Not observed	Surface ice and rock and a small silicate core Ice and minerals [81]	CO_2 atmosphere and questionable presence of life in the salty ocean

(continued)

Table 2.3 (continued)

Objects	Liquid water	Ice	Water vapor	Other resources (approximate values)	Comments
Ganymede (moon of Jupiter)	Subsurface salty	Surface ice suspected to surround liquid water	Unknown	Iron and rock core Hydrated salts [82]	Has 2 protective magnetic fields, and thin oxygen atmosphere Candidate for a future human outpost
Europa (moon of Jupiter)	Subsurface warm water rich in minerals	Surface covered by ice	Jets of vapor plumes detected by the Hubble Space Telescope over the south pole	Galileo mission detected clay-like minerals on the surface Hydrates salt minerals [83] Na and K [84]	Suspected to have ingredients required for life
Enceladus (moon of Saturn)	Might harbor a large warm salty ocean	Icy geysers	Unknown	Light organics, CO_2, and amorphous and crystalline water ice [85] Sodium, chlorine, calcium and bicarbonate [86]	Suspected to contain ingredients capable to sustain life
Titan (Saturn satellite)	Possibly subsurface ocean	Surface covered by ice water	Present [87]	Surface shaped by liquid ethane and methane	Earth-like with an atmosphere. A potential for a future outpost
Pluto and its moon Charon	Suspected to harbor an ocean	Significant amounts of surface ice	Not detected yet	Possibly silicates	Pluto atmosphere is 90 % N_2 and 10 % methane
Kuiper Belt objects		Significant ice water stores		Composed mostly of methane, ammonia and water	Home of the dwarf planets Pluto, Haumea, and Makemake

USGS United States Geological Survey, *MRO* Mars Reconnaissance Orbiter

Box 2.15 Cryovolcanism
An event marked by the ejection of liquid or vapor plumes of water, ammonia or methane from the solar system's icy moons and objects in the Kuiper belt. It has been suggested that tidal friction, or a radioactive decay, beneath the icy surface generate enough energy to cause melting and increase pressure necessary for such eruptions.

Geysers have been observed, or show features suggestive of, on *Europa, Ganymede, Miranda. Sharon, Titan,* and *Triton* [94–96].

Human missions to Saturn must await new technological breakthroughs in propulsion, self-sufficiency, and life support. Titan may be the best location for a future outer-planet human outpost.

Uranus and Neptune

The *Voyager-2* "fly-bys" in January 1986 and August 1989 found Uranus and Neptune to be as fascinating and enigmatic as the other planets. In addition to five known moons, Voyager-2 discovered ten previously undetected satellites around Uranus, two of which are "shepherd" satellites within a system of rings darker than those around Jupiter and Saturn. Neptune and Uranus are denser than Saturn and Jupiter. This may mean that they are compositionally different, containing methane in addition to hydrogen and helium. New data raise the possibility that, at the extreme temperatures and pressures of these planets, hydrogen and helium form a solution that is denser than either component.

Both planets and their moons contain resources that can provide logistics for robotic and human missions, venturing into the Kuiper belt and beyond. Such missions are probably decades away and will not materialize until the twenty-second century.

Uranus

Uranus is a giant planet orbiting the Sun at a distance of 2.9 billion kilometers, 19.9 AU, surrounded by 13 rings [99]. Uranus is an icy object. The small rocky core is surrounded by dense icy water, methane, and ammonia materials. Uranus' atmosphere consists of hydrogen, helium, and methane, which gives it a blue color tint. This planet has the largest tilt angle, with the axis of rotation almost in the plane of its rotation around the sun. Uranus rotates on its axis every 17.24 h. A complete tour of the Sun takes about 84 Earth's years. Winds blow faster than the planet's rate of rotation and from east to west. Uranus has an internal magnetic field, which, unlike that of Earth, is tilted markedly with respect to the axis of rotation. The minimum atmospheric temperature reaches −224 °C, making it the coldest planet in the solar system.

Uranus has 27 moons, each unique and with different geological histories [100]. All have an upper icy layer; however, underlying geologic activity is indicated by fault lines and other linear features. Impact craters have interacted with the geologic activity and the flow within the ice layers to give each satellite a different appearance. The satellites seem to have larger ratios of rock to ice than would be expected from previous models of the origin of the solar system.

Neptune

Voyager-2 discovered six small satellites orbiting Neptune in addition to the two that were known. Neptune orbits the Sun in 165 Earth's years at a distance of 4.5 billion kilometers or 30.07 AU. It shares with its sister planet, Uranus, similar atmospheric and core composition. Neptune has 13 moons and six rings. Atmospheric wind velocities range from 600 m/s at the equator to 300 m/s (estimated at or more than 2100 km/h) in the polar regions. *Voyager* detected atmospheric clouds and a giant dark spot, which was a short-lived massive storm. "Scouters" are white-colored smaller and fast-moving storm systems. Dual internal and external origin of carbon monoxide in the atmosphere has been reported [101]. Neptune rotates on its axis at a nearly Earth-like 28°44′ every 18.5 h. Its magnetopause seems to interact with the solar winds [102].

The larger moon, *Triton*'s surface and mantle is mostly frozen nitrogen and ice-water, reflecting much of the sunlight and is one of the coldest objects in the solar system (about −240 °C). A rocky and metal core forms one-third of its mass [103]. Triton is the only moon in the solar system circling in a direction opposite to the planet's rotation. Triton is relatively young and exhibits *cryovolcanism,* ejecting a mixture of liquid nitrogen, methane and dust plumes, as high as 8 km and lasting many months [96]. Triton and Pluto are similar in composition. Some scientist believe that Triton was a dwarf planet captured into Neptune's orbit during a close approach [104].

At the Edge of the Solar System

Dwarf Planets

There are five officially recognized dwarf planets in our solar system, they are *Ceres*, *Pluto*, *Haumea, Makemake* and *Eris*. With the exception of Ceres, which is located in the asteroid belt, the other dwarf planets are found in the outer solar system. The NASA space probe *New Horizons* reached Pluto on July 14, 2015. Pluto has a tenuous, nitrogen, methane and carbon monoxide atmosphere that is escaping the planet's weak gravity. This atmosphere seems to appear when the planet is closer to the Sun and its surface is heated and is suspected to freeze and fall to the planet surface when it is colder. Pluto and its larger moon *Charon* show evidence of complex features, glacial flow, and possible *cryovolcanoes* [105]. The planet's surface is covered with ices of water, methane, carbon monoxide, nitrogen, and ammonia, and possibly *tholins*[13] [106, 107]. Possible evidence for atmosphere and clouds have been suggested [108, 109]. Pluto's smaller moons *Styx, Nix, Kerberos*, and *Hydra,* are irregularly shaped, fast-rotating, and exhibiting bright surfaces [110].

The Kuiper Belt and Oort Cloud

The discovery of a dwarf planet, *Sedna*, in 2003 placed the edge of the solar system at a distance of 962 AU from the Sun. The *Kuiper Belt* and the *Oort Cloud* extends that distance at about 100 thousand AU. The Kuiper Belt is located beyond the orbit of Neptune from about 30 to 55 AU, with the Oort Cloud boundaries estimated between 5000 and 100,000 AU. The discovery of 2012 VP113 and the possibility of another Object V774104, reported in 2015, with orbits beyond that of Pluto, has rekindled the discussions on the size and extent of the solar system [111, 112].

The known icy world and comets in belts harbor objects much smaller than the Earth's moon. *Long-period* comets, orbiting the sun around 200 years, are from the Oort Cloud. *Short-period* comets, which orbit the Sun in less than 200 years, originate in the Kuiper Belt. Objects within these two belts do not have rings.

There are some hundreds of thousands of icy bodies larger than 100 km in length, and an estimated trillion or more smaller comets within the Kuiper Belt. The Oort Cloud may contain more than a trillion icy bodies [113]. It has been postulated that the comets are the source of Earth's building blocks and water [114]. Several dwarf planets within the Kuiper Belt have moons.

Infrared spectral observations indicates that portions of the interstellar media exist in the form of dust particles, 0.1 μm in size. Perhaps some of these interstellar particles are constituents of comets, which represent primordial matter that formed on the boundary of the solar system. Amino acid carrying cosmic dust [115] and interstellar *iso-propyl cyanide,* a carbon-bearing molecule, reported in 2014 in a giant gas cloud called Sagittarius B2, a star formation region of our Galaxy [116], are potential clues of the abundance of life in the Universe (Box 2.16) [117].

[13]Complex organic molecules are suspected to be present in the atmosphere of other solar system objects, such as Titan, and used by some bacteria as a source of carbon [106].

Box 2.16 Life under Extreme Conditions of Space

The Surveyor 3 camera, brought back by the Apollo 12 crew, showed evidence of *Streptococcus Mitis*, surviving the pre-launch sterilization process on Earth and 2-year sojourn under the extreme conditions of the Moon. *Source* [117]

Astrobiology and the Search for Extraterrestrial Intelligence

Astrobiology

We live in a universe populated by an estimated 100 billion galaxies. Each galaxy contains more than 100 billion stars, most harboring planets—some in the habitable zone. Water is the most abundant compound in the universe and the Solar System is no exception (Table 2.3). While hydrogen and helium, produced by the Big Bang, are the most abundant elements, carbon is also relatively more common. Carbon binds with many other elements to form complex compounds and is the key ingredient for all life on Earth. Some scientists suggested an alternative biochemistry process for life [118].[14] Some scientists proposed that life on Earth is of extraterrestrial origins, and epidemics, delivered by comets or asteroids [119–121].

The post "Space Race" era, and the discovery of the abundance of life-building elements, gave way to a new interdisciplinary query effort. This effort was invigorated by the Miller and Urey[15] laboratory experiments, testing the chemical origins of life under simulated Earth's early conditions [122, 123]. In 1960, Joshua Lederberg[16] introduced the term *exobiology*—a scientific endeavor of the NASA's Life Sciences Division. The program funded research into the early life and specifically microbial adaptation to Earth's extreme environments and survival under conditions of space [124].

In 1998, NASA transferred the exobiology program to the Space Science Office to integrate the ground-based and space research efforts. The discipline was renamed *Astrobiology*.

The successful investigations of Halley's comet by the Soviet *Vega* spacecrafts, the ESA *Giotto* missions in 1986, the Hayabusa asteroid sample return in 2005, the 2014 *Rosetta/Philae* lander, *ICE*, *Stardust* and *Contour* missions provided together a wealth of information on the origins and nature of the Solar System, including the abundance of

[14]Carl Sagan astronomer, science popularizer, and science communicator (1934–1996).

[15]Stanley Miller (1930–2007) and Harold Urey (1893–1981).

[16]Joshua Lederberg biologist and Nobel Prize Laureate (1926–2008).

Box 2.17 "Today, rock 84,001 speaks to us across all those billions of years and millions of miles. It speaks of the possibility of life. If this discovery is confirmed, it will surely be one of the most stunning insights into our universe that science has ever uncovered. Its implications are as far-reaching and awe-inspiring as can be imagined. Even as it promises answers to some of
our oldest questions, it poses still others even more fundamental."

Remarks by President Clinton
August 7, 1996
South Lawn of the White House

precursor compounds to life. The NASA *Stardust* mission collected and returned dust samples from the coma of the comet Wild 2. Analysis showed that the dust contained the amino acid *glycine*, one of the essential elements in all known life forms on Earth.

A number of meteorites ejected from the planet Mars, by collisions with comets or asteroids, continue to be found on Earth. The composition of these rocks is similar to the compounds identified by the Mars rovers. In 1996, a group of scientists reported biogenic presence in the *Allan Hills 84,001*(ALH84001) meteorite. The finding was announced by the U.S. President (Box 2.17), and is the source of continued debate in the scientific community.

Astrobiology and its institute continue to play a central role in the planning for future robotic missions in the search for extraterrestrial life and best visit sites for human missions.

The Search for Extraterrestrial Intelligence Project

In 1960, Frank Drake performed the first Search for Extraterrestrial Intelligence (SETI) experiment, named *Project Ozma*. He used a radio telescope to listen for radio transmissions from *Tau Ceti* and *Epsilon Eridani,* trying to detect radio transmissions from other civilizations, in the frequency range close to the hydrogen and hydroxyl radicals spectral line. This region is designated a "water hole" and assumes that water-based intelligent life will use this mode of communication. In 1971, NASA funded Drake and other scientists to determine whether coherent radio signals emanate from other solar systems—signals that might indicate the presence of intelligent life [125]. Unfortunately, the funding for this project was cancelled by the U.S. Congress in 1993, but continued with private funding as a SETI Institute [8]. Positive results from the astrometry or SETI programs could have significant societal and scientific implications, providing a new impetus to future interstellar travel. This would be a very long-term goal, as it would require acceleration to high velocities and very long trip times. Hazards of the interstellar media must be countered and new levels of system autonomy and reliability must be achieved.

Box 2.18 NASA 2015–2030 NASA Near-Term Exploration Objectives

NASA envisions 3 steps for human exploration beyond the LEO using the SLS/Orion capability:

1. *Earth reliant* phase using ISS to develop key human support technologies through 2025 (estimated date)
2. *Proving ground* phase to test technologies and operational capabilities. This phase will include human exploration beyond the low Earth orbit. This will consist of short forays to the Cis-Lunar region, Asteroid Redirect Mission to return samples and test logistics and resupply capabilities. This phase will begin with the launch of SLS in the 2018–2019 time frame and the *Robotic Redirect Asteroid* mission to bring a large sample to the *proving ground* in 2020.
3. *Earth independent* phase to develop surface habitats and in situ resource harvesting. Missions will include visits to Mars and its moons.

Obviously this is an ambitious program and is subject to modifications based on the U.S. President's Space Policy, appropriation of adequate funding, and contributions from commercial and international partners.

Source: [125]

NASA Strategic Principles for Human Exploration of the Solar System and the Search of Extraterrestrial Life

NASA strategic planning horizon for human exploration of the solar system continues to evolve based on ever-changing U.S. President's Space Policy and the funding made available by the U.S. Congress. The near-term objectives of the human exploration program are tied to the development of a new space transportation capability and infrastructure, taking into consideration opportunities for the private sector and international participation. Current post Space Shuttle era (beyond LEO) objectives are driven by the scientific knowledge gathered from the robotic explorers, astrobiology, and the role of human presence that is required to enhance scientific returns (see Box 2.18 for near term objectives) [126].

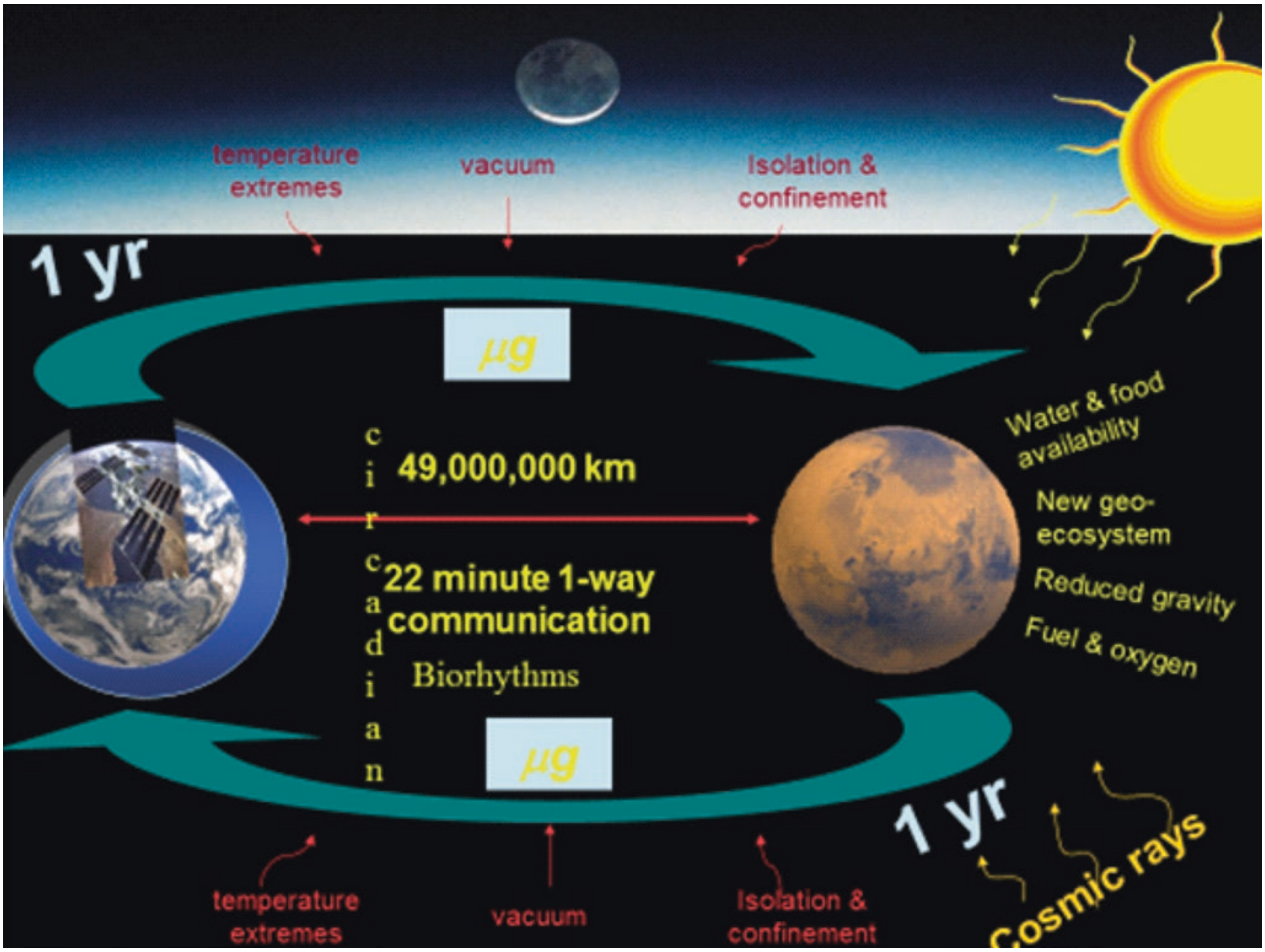

Fig. 2.13 Mars mission planning and major environmental risk factors (Courtesy NASA)

However, the fundamental principles for long-term human exploration goals remain consistent for several decades and can be summarized as follows:

1. Exploration enables science by leveraging robotic expertise for human missions.
2. Integrated human and robotic missions to incrementally allow more complex missions.
3. Incremental buildup of exploration infrastructure and capabilities, and
4. Significant international and commercial participation [127].

Planning for human exploration class involves understanding of the operational environment, and identification of the health risks induced by the environment and those posed by the engineering design. Mitigation of the risks depends on the availability of appropriated funds, technology readiness, national imperative, societal values, and ethical considerations. Exploration of the planet Mars and the search for past or present life remains one of the major objectives and stepping stones to autonomy and human space settlements. Transit to, sojourn on, and return from Mars presents significant unsolved health hazards and technological challenges. A notional representation of a planning scenario, and major risks, such as microgravity, isolation, time scale and radiation exposure are shown in Fig. 2.13. The 2015 NASA human exploration planning horizon envisioned a systematic transition from the ISS research to operations in the lunar orbit, possibly a lunar base, asteroid capture and beginning of Mars missions. Options for Mars exploration and required technologies are detailed in several publications [126, 128, 129].

Box 2.19 Suggested Ethical Principles for Planetary Crewed Missions

Ethical principles of *justice, priority to the worst off* or *fair shares*, used on Earth, are difficult to apply to space exploration situations. *Maximization*, and to some degree *equity* are more suitable principles for space exploration. Thus the purpose of ethics in space medicine is to maximize successful health outcomes for all crew members. In addition, the risk reduction strategy using the maximization approach should also address the long-term explorer's health and quality of life beyond the successful accomplishment of the mission objectives. In some instances, it will be impossible or unwise to use all the medical resources of the expedition to administer care to a seriously ill or injured crew if resupply or timely rescue mission is not possible. Alleviation of suffering based on a triage principle or likelihood to survive, and deciding that some severely injured people should not receive care because they are unlikely to survive might be indicated in such situations [131].

Ethical Considerations in Human Exploration of the Solar System

Human health and performance is affected with increasing duration exposure to extreme environments of space (see Chap. 3). In space, biological changes are dynamic and on occasion unpredictable. Most of the crew health preventive interventions are implemented before the start of a mission to ensure that astronauts are launched "healthy" and in the best possible physical condition. This approach, by itself, is effective for short-duration missions, but might not be adequate for extended-duration planetary missions. In planetary travel, rapid return to Earth might not be possible and access to medical care is limited to the available resources onboard the spacecraft. Adequacy of available resources to address unforeseen health and medical risks that could emerge as the exploration proceeds should be included in the provision of resources prior to mission start. Though a medical professional might be a member of a small crew (usually 5–7 individuals), stowage and weight constraints will limit the extent and capabilities of the medical services. In some instances, it will be impossible or unwise to use all the expedition medical supplies to administer care to a gravely ill or injured crew. Sustaining health and well-being of the remainder of the crew is also a major consideration in provided care.

Until 2006, ethical principles for space exploration were primarily focused on issues of medical information confidentiality and protection of the subject's rights (astronaut) in research [130, 131]. In 2006, an expert panel concluded that carefully prioritized, scarce medical resources, based on principles of triage and the wellbeing and safety of the remainder of the crewmembers, is the most appropriate ethical approach when capabilities and logistics are constrained (Box 2.19) [132].

In addition, communications back to Earth, over vast distances, might not allow enough time to involve and consult all the stakeholders in the triage or scarce resource allocation decisions. Thus the expedition commander and the expedition medical officer, in consultation with the remainder of the crew, will be responsible for the ultimate decision.

Clear policies and protocols for medical care decisions should be formulated prior to the mission start with the participation of the crew, families, and other stakeholders, in consultation with a bioethicist. Such protocols should be explained to the news media and the public to ensure that health risks are well understood.

In 2014, the Institute of Medicine (IOM) of the National Academies addressed the ethics of exceeding medically acceptable radiation exposure standards in extended-duration space missions [133]. The IOM concluded that "…the only ethically acceptable option that could allow for increased risk exposures in the context of long duration and exploration space flights is granting an exception to existing health standards. The committee believes that exceptions to health standards should be considered on a mission-by-mission basis and used in very limited circumstances following the ethics-based framework recommended." NASA has accepted this recommendation [134].

Genetic predictive screening is now possible for some diseases [135]. In the U.S., while the use of such screening is performed by expert clinicians and counselors with patients' consent, the use of genetic screening in the workplace is controversial and has been challenged in legal settings [136]. Using predictive genetic information as a decision tool for selecting interplanetary crews,[17] to minimize chances of illness, is controversial, especially in light of the U.S. Genetic Information Nondiscrimination Act of 2008. Some societies attempted to interpret this legislation to identify conditions and situations under which genetic testing can be conducted in the workplace [137]. This interpretation is not uniformly implemented in the private sector because of the cost of workers acceptance. Commercial space activities may stimulate

[17] As of 2016, and with the current level of technology maturity, such missions do not allow a timely return to a definitive care facility on Earth, following crew health stabilization in space.

further ethical reviews and legislative actions as the technology advances and the private sector starts to expand [138].

As of 2016, international agreements on the bioethical approach for space research are successfully implemented for the ISS (see Chaps. 1 and 3). The existing process can serve as a model for addressing future ethical issues in space medicine practice.

Legal Framework and International Agreements for Exploration and Commercial Development of Space

The Soviet Union *Intercosmos* program, within the USSR Academy of Sciences, was created to accommodate international scientific endeavors and allow participation of crew members selected from other countries. Since 1978, the *Salyut* and *Mir* orbital stations provided a useful platform for such activities. Crew members from many countries in Europe, the Americas, and Asia took advantage of this opportunity. Starting in 1998 the Russian Federation Space Agency accommodated paying private customers to fly in space and also visit the ISS for short periods of time.

The U.S. Space Shuttle program developed flight opportunities for non-career astronauts, designated as *payload specialists*, from the international community and the U.S. industry, under collaborative agreements. The NASA Space Flight Participant Program allowed civilians with unique perspectives or skills, such as Congressional sponsors Senator Edwin Jacob "Jake" Garn[18] and Representative Clarence William "Bill" Nelson II,[19] to venture into space. Under the Teacher in Space Project, NASA selected Christa McAuliffe to participate and conduct educational activities in space. The Space Shuttle *Challenger* disaster ended the space flight participant program. Legislations and agreements continue to evolve. The sections that follow outline the status of the legislations, conventions, and agreements as of 2016.

Legislation (U.S.)

The U.S. federal space research and exploration program has been guided by the National Aeronautics and Space Act of 1958 (Public Law 85-568). This act has been amended several times and in 1998, to further encourage commercial space industry, the U.S. Congress passed a Commercial Space Act (Title II—P.L. 105-303). The Commercial Space Launch Amendments Act of 2004 (49 U.S.C. § 7-1-1etseq) further clarified the requirements governing the licensing and regulation of commercial human space flight, under the oversight of the U.S. Federal Aviation Administration (FAA) in the Department of Transportation (DOT). This act permits the FAA to issue regulations to protect the safety of commercial space crews and space flight participants. The follow-on Spurring Private Aerospace Competitiveness and Entrepreneurship Act (PubL114-90) of 2015 addresses guidelines for US citizen to engage in the commercial exploration and exploitation of "space resources." These guidelines are restrictive and do not extend to biological life and sovereign or exclusive rights or jurisdiction over, nor the ownership of, any celestial body to preclude violation of the Outer Space Treaty.

Several U.S. states enacted laws providing incentives to emerging commercial space transportation companies. These incentives include typical financial support, such as lowered taxes and infrastructure assistance (Virginia's 2008 Zero G Zero Tax Act), and tax exemptions for certain space launch-related business activities [139]. In contrast, Virginia's 2007 Space Flight Liability and Immunity Act [140] extends the FAA's regulations on informed consent and further clarifies the limits on liability to companies providing human space flight. The FAA publication entitled "State Support for Commercial Space Activities" describes these legislations [139].

International Legislations and Agreements

Legislation

In 1967, in anticipation of ever-expanding human visits to other planets, the United Nations adopted a treaty establishing the "Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies" [141, 142]. This treaty, also known as the *Space Treaty*, is the basic legal framework of international space law. The treaty covers both robotic and crewed missions. The treaty recognizes that space will be used for peaceful and scientific endeavors for the benefit for all, recognizes as ambassadors of humankind, and specifically prohibits the use of outer space and celestial bodies for:

1. Testing weapons,
2. Establishing military bases, or conducting maneuvers, and
3. Governments from claiming a celestial resource such as the Moon or a planet.

The United Nation's International Civil Aviation Organization (ICAO) has proposed to enact space travel regulations by 2019 [143]. While not binding, such regulations can serve as guidelines for nations engaged in, or planning for, space tourism.

[18] STS 51 D launched in 1985.

[19] STS 51 C launched in 1985.

Fig. 2.14 Mobile quarantine facility: Apollo 11 Crew and President Nixon (Courtesy NASA)

International Agreements

Planetary protection has been developed within an international framework by the science community as a guiding principle to minimize a chance of biological contamination of celestial bodies and the Earth as a result of interplanetary missions. The primary intent is to preserve, as much as feasible (specifically biology) the existing environment of the target celestial bodies until they can be studied in detail. There are two major considerations:

1. **Forward contamination** is the transfer of Earth's life (primarily microorganisms) from Earth to another celestial body, and
2. **Back contamination** is the transfer of extraterrestrial organisms back to the Earth's biosphere.

The Space Treaty Article IX specifically calls for preventing both forward and back contamination through adoption of proper precautions and procedures. This article serves as the basis for the Committee on Space Research (COSPAR) to develop recommendations for avoiding interplanetary contamination. COSPAR, on the mission profile, has developed five categories of recommendations [144]. Some of the protocols require dry heat sterilization of components, or whole spacecraft, of robotic missions and assembly under sterile environments. Sample return missions fall into the category V and require special precautions [145]. The crews and samples of Apollo 11, 12 and 14 were quarantined in special transport facilities (Fig. 2.14). Lunar samples were housed in special biosecurity facilities for further analysis. The crew quarantine was discontinued for subsequent Apollo Lunas Missions, when no pathogens were found in the returned samples. NASA and other space agencies maintain an Office of Planetary Protection [146] to oversee policies and develop protocols and standards [145]. The activities of this office are closely coordinated with the NASA Astrobiology program and, in the case of human space flight, with the Chief Health and Medical Officer.

Core principles, validation of the information and stakeholder's involvement, for handling the discovery of intelligent and non-intelligent extraterrestrial life requires continuous refinements and ethical reviews [147].

Conclusion

Human exploration of the Solar System, and particularly missions to the planet Mars, presents serious health and medical challenges. Understanding the exploration environment to address medical risks, develop health maintenance systems, design spacecrafts, surface habitats, logistics, and human-machine interfaces is essential to crew health, safety, and mission success. Space medicine practitioners are, and will continue to be, intimately involved with space crews, mission planners, and aerospace engineers to address risks, identify solutions, and conduct trade-off assessment of cost, weight, and capabilities of different human support systems. This trade-off should be conducted with full understanding of implications of ethical considerations of scarce resource allocation. Safe and successful travel and living away from planet Earth, commercial human space flight, prospecting for extraterrestrial resources, and establishing human outposts will require further insights into societal and ethical implications [148]. Interactions with space scientists to understand the space exploration environment is critical to mission success. NASA has successfully integrated robotic and human mission objectives to maximize the knowledge base for human exploration.

Key Points to Remember

1. Increasing distance from Earth is associated with new and increasing health risks,
2. ISS is providing a test bed to study the health effects and risks of microgravity in missions of longer than 1-year duration,
3. Robotic missions and space sciences provide invaluable resources to the understanding of the exploration environment, and
4. Future human missions will involve international participation requiring space medicine experts to understand the nature and scope of different treaties, laws, regulations, and practices.

Self-Study Questions

1. What are the possible planetary protection implications of missions to planet Mars?
2. Describe the planetary protection requirements for a NASA Asteroid Redirect Mission?
3. Address potential health risks from an extended stay on Mars surface.
4. Expand on the health risks from spacecraft collision with space debris or interstellar particle.
5. Review the radiation risks on the planet Mars surface.
6. What are the long-term health effects of Lunar and Martian dust?

Case Study

Learning Objective: Explore complex divided loyalties; ethical dilemma in the practice of space medicine [149, 150].

Confidentiality between health care providers and patients is an essential element of mutual trust and successful practice.

In the U.S., the Privacy Act of 1974 [151] and the Health Insurance Portability and Accountability Act (HIPAA) of 1996 [152] govern the protection of patient medical information. NASA as a U.S. federal agency is bound by the guidance provided by both acts. This case study is representative of the handling of the astronaut health information confidentiality in an agency committed to transparency and timely public information dissemination, especially during space missions.

Three hours after achieving LEO insertion, the crew commander of a 16-day space shuttle mission contacts the MCC, at the Lyndon B. Johnson NASA Space Center, and requests a private medical conference (PMC) within 1 h, involving the mission physician and the crew. The PMC is subject to confidentiality and is not transmitted over an open line and not available to the press in the MCC. The mission physician is informed that one of the astronauts is experiencing "space motion sickness," and is unable to perform critical operational and research tasks associated with the activation of on-orbit research activities. Furthermore, the astronaut is not scheduled for a spacewalk until mission day 8. After conferring with the patient using voice, video, and the inputs from on orbit pilot trained as a paramedic, the mission physician determines that the crewmember in addition to vomiting is also experiencing the "sopite syndrome." The pilot astronaut is advised to administer 25 mg of promethazine hydrochloride delivered by intramuscular injection. Additional dose can be used in 12 h and after a second PMC. The physician also recommends increased fluid intake, rest, regular monitoring of vital signs—especially respiration and blood pressure—and avoiding the use of other anticholinergics. The mission commander is confident that the remainder of the crew will be able to handle the duties of the patient without mission compromise or rescheduling the activities timeline.

The mission physician notifies the mission managers of the on-orbit status, on a need to know basis, and cautions the recipients of the confidentiality of the medical information and legal implications. In the meantime, representatives of the press aware of the PMC, and absence of the "sick astronaut" in the on-orbit television transmissions request information on the status of the crew health.

The MCC director consults the crew physician for advice, especially since the next mission press briefing is scheduled to start in 2 h. The crew physician reaffirms that the crew illness does not impact the mission timelines and the medical information will remain subject to non-disclosure. Based on medical and ethics expert information, NASA has adopted the policy of non-disclosure of astronaut medical information and confidentiality in all cases where there is no major mission impacts.

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