

# 2

## THE NEW FRONTIER

*O'er the smooth enameld green,  
Where no print of step hath been,  
Follow me, as I sing  
And touch the warbld string;  
Under the shady roof  
Of branching elm star-proof  
Follow me.*

John Milton, from *Arcades*

**F**AR above the emerald green seas that served as passageways through the Mediterranean, the Polynesian Pacific and to the New World, far above the tremulous canopies of the elm forest and beyond the finest wisps of Earth's life-giving atmosphere sits the Interplanetary Frontier. In crystal clarity, telescopes and space probes have returned photos of the strange environments of other solar-system worlds. Where in nearby space might human settlements best be

established and how might humans and their descendents live in these strange new environments?

Broadly speaking, other than the Earth, there are three different types of environments within our solar system that will be of interest to early space pioneers. There are small, airless worlds such as our Moon, marginally habitable places such as Mars, and mountain-sized asteroids or comet nuclei. From the point of view of future human pioneers and settlers, each has advantages and disadvantages.

We omit from consideration such places as torrid Mercury and Venus and giant worlds such as Jupiter. Although far-future humans or their descendents might learn how to terraform Venus into a more clement, Earth-like world, or disassemble the gas giants to construct hordes of space cities, realization of such speculations lie very far in our future.

### THE MOON AS A HABITAT

Because of its relative proximity, we begin our survey with Earth's single natural satellite, the Moon. Luna is the only solar-system world, other than the Earth, on which humans have walked. Many robotic probes have flown by, orbited, landed upon, or returned samples from the Moon. During 1968–1972, the crews of Apollos 8 and 10 orbited the Moon, Apollo 13 circled the Moon during its aborted mission, and the lunar modules of Apollos 11, 12, and 14–17 landed upon the lunar surface (Figure 2.1).

Following in the footsteps of the Apollo astronauts, future lunar pioneers will encounter an environment vastly different to any on Earth. The Moon orbits the Earth once every month, at an average distance of almost 400,000 kilometers. Contemporary rockets require about three days for a one-way lunar voyage.

Because the Earth has a mass 81 times that of the Moon, lunar gravity is much weaker than terrestrial gravity. Discounting the mass of the gear required to keep a person alive in the Moon's vacuum, a person weighs only one-sixth as much on the Moon's surface as on Earth.

Not only does the Moon *not* have an atmosphere, but water is either very rare or non-existent there. Two space probes—Clementine and Lunar Prospector—have returned preliminary data indicating that water-ice from ancient comet impacts may exist in craters near the lunar poles that are shielded from sunlight. But until this is confirmed and we have a better idea regarding the magnitude of this resource, future lunar colonists must plan to recycle as much of their habitat's water as possible.



*FIGURE 2.1 Apollo 15 astronaut David Irwin works on the lunar rover during an excursion near Mt Hadley. Hollow volcanic lava tubes in this region might someday house human settlers. (Courtesy NASA)*

Because the Moon does not have an atmosphere, one might think that solar energy would be more effective in powering a lunar civilization than it is on Earth. However, because of tides produced by the much more massive Earth, the Moon's rotation rate around its axis is identical to its revolution rate around the Earth. This means that a lunar "day" consists of 14 Earth days of sunlight followed by 14 Earth days of darkness. Because of this factor and the lack of an atmosphere, lunar temperatures are quite variable, ranging from a low of  $-170$  degrees Celsius to a high of  $130$  degrees Celsius.

Unless we restrict human settlement to its polar regions which will benefit from near-continuous sunlight, any permanent lunar residents will have to contend with these temperature variations. Also, some form of energy storage facility or auxiliary power source will be necessary to supplement direct solar energy during the long lunar nights.

Some consider the lack of a lunar atmosphere to be a great advantage for future astronomical facilities based on our Moon. It has been suggested that a radio observatory on the lunar farside would be shielded from terrestrial radio signals by the Moon's limb. However, much larger radio telescopes could be constructed in free space and shielded from terrestrial radio signals by bulk material or simply pointed away from the Earth.

Another possible function for a future human civilization—mining of material for use on the Earth or in space—also has issues. Some have suggested that copious reserves of helium-3, a form of helium ejected from the Sun and of possible significance to a future nuclear-fusion-based economy, exist in usable concentrations in the lunar soil. Although this is possible, concentrations are very low and the Apollo core samples only extended a meter or so into the lunar dust and regolith. We may have to go further—the atmospheres of the giant planets, or the solar wind—to tap into significant helium-3 reserves.

Advocates of lunar mining and science may come into conflict. No matter how clean a mining process, quantities of fugitive lunar dust will be raised above the surface. In the low lunar gravity, these dust grains may remain aloft for many months, partially obscuring the pristine lunar skies sought by some astronomers and contaminating sensitive optical instruments as the dust inevitably falls back to the surface.

Even though volatile material such as water is lacking or very rare on the Moon's surface, methods have been suggested that could be used to catapult mined lunar rock from there. This material might be of use in constructing solar-powered satellites to beam energy to Earth or as cosmic-ray shielding for large space habitats. However, near-Earth objects (NEOs)—a class of asteroids and comet nuclei that approach the Earth—might be a source of higher grade ore and may require less energy to access economically.

## LIVING AMONG THE NEAR-EARTH OBJECTS

Beyond the Moon, the next possible destinations for our space pioneers are the NEOs. The main source for these Earth-approaching objects, most of which do not exceed a kilometer in size, are the asteroids and comets.

Left over from the solar system's formation almost five billion years ago, asteroids are rocky and stony space objects typically found in the Asteroid Belt between the orbits of Mars and Jupiter. Gravitational perturbations have altered the positions of some asteroids—a number co-orbit with the giant planets or have been captured as their satellites, others have been thrown into Earth-crossing trajectories. The largest asteroid, Ceres, is 914 kilometers in diameter. Only about 150 of the 10,000 or so known asteroids are greater than 100 kilometers in diameter.

Earth-approaching asteroids tend to be much smaller. Astronomer John Remo estimates that there are about 20 NEOs with diameters greater than

5 kilometers, around 2,500 with diameters in the 1–2 kilometer range, and approximately 100,000 with diameters between 0.1 and 1 km.

A significant fraction of the NEO population is of cometary rather than asteroidal origin. Comets are multilayered objects left over from the solar system's origin. Around a rocky nucleus perhaps 20 kilometers in diameter are layers of volatile ices—water, methane, and ammonia. Many comets also have a layer of dust overlaying the volatiles. When a comet enters the inner solar system, solar heating evaporates some of the volatile ices. A typical comet making its inner solar-system passage is observed to have multiple tails of dust and volatiles, pushed by solar radiation pressure away from the Sun. Although a comet tail might be 100 million kilometers in length, it is so tenuous that all its material could be packed into a steamer trunk.

Comets usually reside in two reservoirs. Oort Cloud comets typically orbit the Sun at distances of a trillion kilometers or more. Those in the Kuiper Belt typically orbit a few billion kilometers from the Sun. The planet Pluto is the largest known Kuiper Belt Object (KBO).

Oort Cloud comets are scattered sunward during rare passages of other stars through or near the Oort Cloud. KBOs enter the inner solar system (sometimes taking up residence as NEOs) after gravitational perturbations by the giant planets, especially Jupiter and Saturn.

Since many NEOs approach the Earth at distances measured in millions of kilometers, much less energy is required to reach them than more distant celestial objects such as Mars. Trajectories have been designed that allow human exploration of some NEOs using current propulsion technologies with round-trip durations of a year or less.

Human colonists amid the NEOs will have to contend with the fact that these low-mass objects have surface gravities about one thousand times less than that of the Earth. To avoid bone degradation in the milligravity environment of a NEO, human colonists will be obliged to rotate their space habitat to produce artificial gravity. Radiation shielding for their habitat should be relatively easy to obtain from the upper NEO surface layers. Radiation is reduced or eliminated by placing lots of matter between the person and the radiation source. Since many NEOs have ample reserves of water and other volatiles, NEO colonists have less trouble with this requirement than their colleagues on the Moon.

In all likelihood, a human space habitat would use a NEO (or many NEOs) as a resource base. Unlike St Exbury's *Little Prince*, NEO colonists will probably live near a NEO, or within a hollowed-out NEO, rather than on one.

## THE LURE OF MARS

Using chemical, solar, or nuclear rockets, 6–9 months are required for a one-way voyage to Mars. Fourth from the Sun and never closer to the Earth than 56 million kilometers, the Red Planet has baited human astronomers and fiction authors for centuries and tantalized space explorers for decades.

Early telescopic observers learned that Mars has polar caps, like the Earth. Some detected seasonal changes and occasional clouds. At the limits of resolution, a number of influential nineteenth-century astronomers reported a network of fine lines on the planet's surface—the legendary canals.

By the early twentieth century, these observations and science fiction of authors, including H.G. Wells and Edgar Rice Burroughs, firmly entrenched the idea of a Martian civilization in the human psyche. On this small and arid world, a fictitious ancient civilization had constructed canals to divert water from the polar regions to the equatorial cities. But as the atmosphere was escaping and the water reserves were emptying, Martian interplanetary imperialists began to turn their attention to the third planet from the Sun, our fertile Earth. Fortunately, it is now evident that the canals were illusory and that indigenous higher life forms do not exist on Mars.

Unlike the Moon with its month-long “day” and the NEOs with their widely variable rotation rate, the Martian “Sol” is only slightly longer (40 minutes) than the terrestrial day. But that's where the similarity between the two worlds ends.

Mars has an exceedingly thin atmosphere, with a surface pressure less than 1% that of the Earth and a surface gravity about 38% that of Earth. Although the polar caps do indeed have some water ice, their major constituent is dry ice—frozen carbon dioxide. This is not surprising since CO<sub>2</sub> is the predominant gas in the planet's thin atmosphere and frigid temperatures near the Martian poles are low enough to cause it to freeze.

Impact craters abound on Mars, as do enormous ancient volcanoes. One of these giants, Olympus Mons, dwarfs Mount Everest in both girth and height. Another major feature is Vallis Marineris, an equatorial canyon system far greater in size than North America's Grand Canyon.

Most tantalizing of all Martian surface features are the unique landforms produced by ancient rivers and seas. At some time in the distant past, Mars shimmered with abundant surface water, perhaps resembling a somewhat smaller version of the Earth.

Recent evidence from Martian rovers and orbiters indicates that some portions of Mars have been water-covered comparatively recently. Water may indeed be common in subsurface layers of the planet's regolith. One trace constituent of the Martian atmosphere is methane, which is a byproduct of terrestrial biological processes. This data, in combination with the ambiguous bacteria-like structures found in the mid-1990s in a meteorite from Mars, has led many exobiologists to the conclusion that Martian life was abundant in the past and may still exist in subsurface locations or caves today.

Future robotic and human expeditions to the Red Planet are planned, many of which will search for life on Mars or return samples directly to the Earth. Hopefully, we will know before too many decades have elapsed whether Gaia (Mother Earth) has a near neighbor in the solar system.

The search for Martian biology is a double-edged sword for would-be colonists of this planet. Early human expeditions to the Red Planet will almost certainly be driven by astrobiology. But if Martian life is actually discovered with a tenuous foothold in caves or below the planet's surface, a furious ethical debate is sure to ensue. Some will argue that Mars should be declared a preserve for indigenous Martians, no matter how primitive and that the human technological ability to cross the void is not a divine right to impose our biology on a distant biosphere. Others are sure to respond with the Darwinian argument that terrestrial life forms, having demonstrated the ability to survive interplanetary travel, are more fit to survive than the residue, stay-at-home Martians. Also, as happens on the Earth, where life that adapted to extreme environments such as the polar caps, deep-ocean floor, or upper atmosphere, can coexist successfully with our form of abundant surface life, perhaps Martian and terrestrial life forms can successfully share the Red Planet.

If people do ultimately settle on Mars, the first settlements may be shielded from cosmic radiation by Martian soil offering shelter not provided by the planet's atmosphere. The domed cities of science fiction may be constructed later as terraforming efforts begin the thickening of the atmosphere. After hundreds or thousands of years, perhaps with the aid of greenhouse gases imported from the Earth, the Martian atmosphere might be thick enough and the surface warm enough to support free-standing bodies of water, forests, parks, and outdoor agriculture. Although Mars may never be a twin of the Earth, it may ultimately become a second planetary biosphere in Sol's system.

## SETTLING THE OUTER SOLAR SYSTEM

Beyond Mars, there are ample opportunities for human expansion. The tiny Martian satellites, Deimos and Phobos, could be developed as refueling depots and way-stations for Mars-bound explorers and colonists. Similar to a class of asteroids resembling carbonaceous chondrite meteorites, these objects are probably extinct comet nuclei captured by Mars and, therefore, well equipped with water and other volatiles.

Farther out, between the orbits of Mars and Jupiter, are the main belt asteroids. These will serve as resource bases for human space settlements as human civilization expands into the outer solar system.

Next out from the Sun is the giant planet Jupiter, which has more than 300 times the mass of the Earth. Jupiter, a very strong radio emitter (strong enough, in fact, to be heard on Earth in the shortwave radio band at 20.1 megahertz), is encircled with radiation belts more lethal than the Earth's Van Allen Belts. It's four large satellites—Callisto, Europa, Ganymede, and Io—are interesting and exciting worlds with unique surface features. Io has giant, continuously erupting volcanoes that alter the landscape at a prodigious rate. Europa is apparently encircled by a water ocean many kilometers deep and covered with an ice pack—tantalizing space probe imagery reveals that some parts of this ocean are not frozen. Ganymede and Callisto have features indicating both water deposits and impacts by smaller celestial objects. Sadly, Jupiter's intense radiation belts may preclude widespread human settlement among these interesting little worlds.

The sixth world from the Sun, Saturn, is like all the giant worlds, attended by a system of rings that were probably formed when asteroids or comets approached the planet too closely. But unlike the rings of Jupiter, Uranus, and Neptune—which are only visible from space probes or space telescopes—Saturn's rings are easily viewed using binoculars or small telescopes. Although we may never attempt to live in the alien environments of Saturn space, the Huygens probe recently touched down on the surface of Saturn's large satellite Titan, revealing a bizarre landscape perhaps not dissimilar to the primeval Earth.

Next out are the smaller giant worlds of Uranus and Neptune. It remains to be seen whether we will ever live on the satellites attending these majestic gas balls in the frigid fringes of the solar system, but some day we might mine their atmospheres for isotopes such as helium-3, which will be of great value to a thermonuclear-fusion-based economy.

Beyond Neptune we come to the realm of the Kuiper Belt Objects (KBOs). Pluto, which requires almost 250 years to complete one revolution around the Sun, is one of the largest known KBOs.

The KBOs contain ample reserves of frozen water, methane, and ammonia. Therefore, intrepid far-future humans equipped with low-mass solar collectors to focus the emanations from the distant Sun could, with effort, settle these small, frigid worldlets. Most of the required technologies for such expansion will have been tried among the much closer NEOs and main belt asteroids. Additional interest in exploration is generated by evidence that one source for the short-period comets that occasionally whack the Earth with devastating consequences is the Kuiper Belt.

Beyond the Kuiper Belt cometoids is the Oort Cloud, the home range of perhaps a trillion comets. The Oort Cloud comets, some of which range a third of the distance to the nearest stars, are the reefs of Sol's system, lonely sentinels on the edge of infinity. When humans are technically ready to settle this distant realm, their space habitats must be essentially independent of distant Terra. At that juncture, we will also be capable of traversing the greater distances to the nearer stars.

## INTERSTELLAR ENVIRONMENTS

Recent telescopic evidence suggests that many or most stars have planetary companions. Although we cannot reliably detect Earth-like worlds, a multitude of extrasolar Jupiter-like worlds have been discovered. Many of these new worlds have bizarre orbits—circling so close to the parent star that the orbital period is but a few days, or riding extreme comet-like ellipses. But some of the newly discovered solar systems superficially at least, resemble our own. Since both single and binary stars have been observed to possess planetary companions, many of our Sun's stellar neighbors are potential habitats for future star-traveling humans.

The Sun's distance from the Earth is 150 million kilometers or 1 Astronomical Unit (1 AU). Pluto's average distance from the Sun is about 40 AU. If we some day learn to build ships capable of crossing a 260,000 AU (or 4.3 light-years) interstellar gulf, our descendents will be capable of reaching our Sun's nearest stellar neighbor, the triple star system called Alpha Centauri.

Interstellar explorers may choose to ignore the closest member of this trio, Proxima Centauri. A red dwarf star with very low luminosity, Proxima is probably too dim to support life-bearing worlds.

Such is not the case for the two central sunlike stars, Alpha Centauri A and B. The separation between these stars is ample for one or both to have a solar system. Our nearest stellar neighbor may in fact have more than one Earth, and more than one Mars. Many satellites, asteroids, and comets may also grace the Centauri system.

Ships that can traverse distances of 11–12 light-years could explore the systems of Epsilon Eridani and Tau Ceti, our next nearest solar-type stellar neighbors. Although recent observations indicate that Epsilon Eridani may be attended by a Jupiter-sized planet, this system may be too young for life to have evolved on any of its planets or satellites.

As recent observations have revealed that Tau Ceti is surrounded by a very extensive asteroid belt, repeated asteroid impacts may preclude the evolution of advanced life in this system.

We are still new to the game of extrasolar-planet detection. As larger or more capable space and terrestrial telescopes come on line, we will certainly learn a good deal about the environments that await us among the stars.

We have come a long way in the 2,500 years or so of astronomical observations. At the start of the Athenian golden age, the planets were divine entities and the stars were portals to heaven. Now, the planets are worlds more or less like our own and the stars are Suns with their own solar systems. Life may well exist in the reaches of this New Frontier or may be carried there by ships from Earth.

## FURTHER READING

Prospects for further lunar exploration and lunar habitation are discussed by E. Burgess, in *Outpost on Apollo's Moon* (Columbia University Press, New York, 1993). An excellent introduction to the Red Planet is M. Caiden and J. Barbree with S. Wright, *Destination Mars* (Penguin Putnam, New York, 1997).

Many college-level astronomy texts summarize current knowledge of small solar-system bodies and outer-solar-system environments. Especially notable and readable is E. Chaisson and S. McMillan, *Astronomy Today*, 3rd edn (Prentice-Hall, Upper Saddle River, NJ, 1999). For the most up-to-date information on solar-system exploration, consult popular astronomy magazines such as *Astronomy* and *Sky & Telescope*.

Prospects for free-space habitats is discussed by G.K. O'Neill in *The High Frontier* (Morrow, New York, 1977). Use of solar-system resources

to support these future facilities is further investigated by B. O'Leary, in *The Fertile Stars* (Everest House, New York, 1981).

Lots of information on planets of other stars is included in P. Gilster's non-technical *Centauri Dreams* (Copernicus, New York, 2004), which also discusses other possible means of reaching the stars.



$$MR = \text{Exp}(\text{delta } V / V_{\text{ex}})$$

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