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THE SEARCH FOR LIFE IN THE SOLAR SYSTEM*

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ABSTRACT

In this presentation I give an overview of the long struggle to answer the age old question, does life exist anywhere else? The focus will be specifically on the search for life in the solar system, since this is the only region currently accessible to direct investigation. A hundred years ago many people believed that life, possibly even intelligent life, existed at the nearby planets Venus and Mars, and possibly elsewhere. The space age exploration of the planets has radically altered that view. We now know that Venus is a very hostile place, with no possibility for life, and that Mars is almost completely barren and very cold, with little prospect for life. The only remaining possibility appears to be in the interior of some of the moons of the outer planets where, due to an unlikely combination of factors, the conditions may be suitable for life.

Ever since man gazed at the stars, the question must certainly have arisen, are we alone, does life exist somewhere else in the universe? Because of the enormous number of stars in the universe, 300 billion in our galaxy alone, and the likelihood that many of them probably have planetary systems similar to our own, some investigators, such as Sagan and Drake (1), have concluded that life, including intelligent life, should be very common throughout the universe. On the other hand, Ward and Brownlee (2) have recently argued that the conditions for life are so specialized that Earth is most likely entirely alone in having complex life. Although no extraterrestrial life has yet been found, most would agree that the discovery of life elsewhere, even in its simplest microbial form, would be one of the most significant scientific advances in human history.

In this paper I will discuss the history of the search for life in the only region that is currently accessible to direct *in situ* investigation, namely our solar system. As you will see, the history of this subject is riddled with tremendous conflicts and radical revisions in our think-

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ing. I will begin by reviewing the historical developments that led to our current understanding of the solar system, and discuss the concept of a habitable zone, which is the region around the Sun where the temperature is predicted to be favorable for life. Next, I will discuss early ground-based observations that led many to believe that Venus and Mars had living things, and will show how modern spacecraft observations have radically modified our views regarding the possibility of life at these planets. Finally, I will discuss recent spacecraft observations of the moons of Jupiter and Saturn that suggest life may be possible in the interiors of these seemingly hostile moons.

THE SOLAR SYSTEM

The solar system consists of the Sun, the planets, the moons and all the other minor objects that orbit the Sun, such as comets and asteroids. Although the basic picture of planets orbiting the Sun is known to all school children, prior to the seventeenth century the widely held view was that Earth was at the center of the universe, and that the stars and planets all revolved around Earth. This view was based on the model of the Greek philosopher Ptolemy, who lived from about 127-151 AD. Ptolemy's model was basically geometric and involved clock-like motions of the stars and planets around Earth. To account for the apparent non-uniform looping motions of the planets across the sky, the motions were regarded as a combination of two circular motions that revolved at different rates. These motions were called epicycles. Although complex, the epicycle model of Ptolemy accounted for planetary motions reasonably well, especially considering the rather imprecise astronomical measurements available at the time, and was endorsed by the Roman Catholic Church as the official dogma of the church. Because of the church's influence, no other model was even considered for over twelve centuries, until a Polish physician, Nicholas Copernicus, who lived from 1473 to 1543, critically examined the issue. Although Copernicus was a practicing medical doctor, at one time the personal physician of the Duke of Prussia, he developed an interest in astronomy and began exploring the idea that the planets revolve in circular orbits around the Sun. This model is called the heliocentric model. Using simple geometric arguments and existing data he established the now accepted ordering of the planets outward from the Sun, and their approximate distances from the Sun. The average distances of the planets from the Sun obtained by Copernicus are given in Table 1, along with the currently accepted values and various other planetary characteristics such as their orbital periods and rotation periods.

TABLE 1

Orbital and Physical Properties of Planets

Planet	Distance from Sun (in AU)		Orbital Period	Diameter (Earth diameters)	Rotation Period (days)
	Copernicus	Modern			
Mercury	0.38	0.387	88 days	0.38	58.6
Venus	0.72	0.723	225 days	0.91	243.0
Earth	1.00	1.000	365 days	1.00	1.00
Mars	1.52	1.523	687 days	0.53	1.03
Jupiter	5.22	5.202	11.9 years	11.2	0.41
Saturn	9.18	9.539	29.4 years	9.5	0.44
Uranus	—	19.19	84.0 years	4.0	0.72
Neptune	—	30.01	164.8 years	3.9	0.67
Pluto	—	39.53	284.5 years	0.18	6.39

The distances in Table 1 are in Astronomical Units (1 AU = distance from the Sun to Earth, 1.49×10^{11} m). No distances are given by Copernicus for Uranus, Neptune and Pluto, because these planets had not yet been discovered.

Copernicus' heliocentric model clearly provided a much simpler description of planetary motion than Ptolemy's epicycle model. However, because of the influence of the church, the heliocentric model could only be discussed as a hypothesis, and was not to be taught as a proven fact. The status of the heliocentric model changed drastically in 1610 when the Italian astronomer Galileo Galilei (1564–1642) used the first rudimentary telescope to look at heavenly objects. One of his first observations revealed four large moons, now called the Galilean satellites, orbiting the planet Jupiter. His discovery of moons circling Jupiter, which he saw as analogous to the planets circling the Sun, convinced Galileo that Copernicus was correct in claiming that the planets revolved around the Sun. He also discovered that the planet Venus had phases, like the phases of Earth's moon. This observation showed that Venus orbited the Sun inside the orbit of Earth, as predicted by the Copernican model. When he began to openly discuss his new observations, and started giving lectures advocating the Copernican view, he immediately encountered opposition from the church. In 1616 he was ordered by his friend Pope Urban VIII not to teach or advocate the heliocentric model. After much anguish, he publicly announced his support of the heliocentric model in a now famous book "Dialogue on the Two Great World Systems," published in 1632. Because of this direct affront to church dogma, he was brought before a Roman Inquisition and found guilty of disobeying an order of the Pope, and was placed under house arrest until he died in 1642. His book was on a list of forbidden books by the church until as recently as 1835.

Nevertheless, over time his views eventually prevailed. In 1979, more than three hundred years after he wrote the “Dialog,” he was cleared by Pope John Paul II of disobeying an order of the Pope. These historic developments, together with the laws of mechanics and gravity formulated by Isaac Newton (1642–1727), provided the scientific basis for our current knowledge of the motion of all of the planets and moons in the solar system, an essential prerequisite for modern space flight.

THE HABITABLE ZONE

In considering where life might exist in the solar system, it is useful to consider which planets have conditions favorable for life. Of the various conditions required for the existence of life, such as the presence of organic material, liquid water, and a suitable source of energy, one of the most essential is a suitable range of temperatures. Since water is the basic solvent in all living things, the boiling and freezing points of water are regarded as the key temperatures that determine the limits of life as we know it. At Earth most living things have a very poor tolerance of temperatures approaching the boiling point of water, and generally cannot survive at temperatures above about 50°C. On the other hand, if a suitable energy source is available, living things can survive relatively cold temperatures, well below the freezing point of water. It is not uncommon for animals in the arctic to survive at temperatures as low as -60°C. Although some organisms are known that can survive even larger temperature extremes, for our purposes we will regard 50° to -60°C as the temperature range within which life can exist.

Since the intensity of sunlight decreases with increasing distance from the Sun, it is easy to see that the surface temperature of a planet should decrease with increasing distance from the Sun. The exact dependence on distance from the Sun is controlled by energy balance considerations. In equilibrium, the sunlight energy incident on a planet, which varies inversely with the square of distance from the Sun, $1/R^2$, must balance the infrared energy radiated by the planet, which by Stefan’s law varies as the surface temperature to the fourth power, T^4. From this simple energy balance argument it is easy to see that the surface temperature of a planet should vary as the inverse square root of the distance from the Sun, i.e., $T \sim 1/\sqrt{R}$. Unfortunately, the true situation is somewhat more complicated. Clouds and light-colored surfaces like snow and sand reflect some of the incident sunlight, which reduces the amount of sunlight energy absorbed by the planet. Also, atmospheric gases affect the amount of infrared radiation that escapes from the planet. To avoid these complications we often consider an idealized object called a "black body" that is both a perfect absorber and a perfect emitter. A piece of black coal would be a good black body. Using the correct proportionality factor in the equation $T \sim 1/\sqrt{R}$, it can be shown that the temperature T of a hypothetical black body at a distance R from the Sun is given by the straight line labeled "black body temperature" in Figure 1. Note that on a log-log plot such as in Figure 1, the $T \sim 1/\sqrt{R}$ dependence is a straight line. The black body temperatures are seen to vary from a high of about 440°K (167°C) at Mercury, to a low of about 40°K (−233°C) at Pluto. For reference, the currently known average surface temperatures of all the planets are also shown on this plot. With the exception of Venus, which we shall discuss later, the actual temperatures are close to the black body temperature, and in some cases, slightly higher. The average temperature of Earth, for example, is about 30°C higher than the predicted black body temperature, a difference that is attributed to the greenhouse effect.

Next, we consider the range of distances from the Sun for which the predicted black body temperatures are in a range suitable for life. Using our earlier discussed temperature limits of 50° to −60°C, and the $T \sim 1/\sqrt{R}$ black body line in Figure 1, it is easy to see that the corresponding distances from the Sun are approximately 0.70 to 1.62

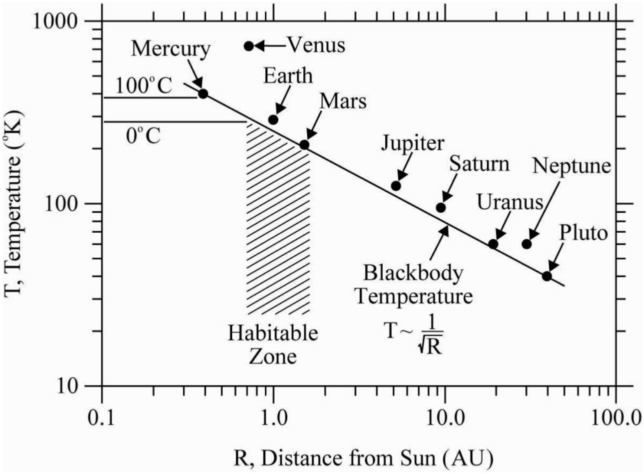

FIG. 1. The predicted black body temperature and the currently known average surface temperatures of the planets as a function of distance from the Sun.

AU. This region is indicated by the hatched region labeled "Habitable Zone" in Figure 1. Since the actual surface temperatures are affected by cloud cover and surface properties, which for the moment we regard as unknown, and since the temperatures at which life can exist are also uncertain, the boundaries of the habitable zone cannot be regarded as precise, but rather as only a rough guide. However, they do appear to rule out life at Mercury, which is extremely hot due to the proximity to the Sun, and at the outer planets, Jupiter, Saturn, Uranus, Neptune, and at Pluto, which are extremely cold due their large distances from the Sun. Only three planets, Venus, Earth and Mars, fall within the habitable zone. Since we already know that Earth has abundant life, in the next two sections we will focus on the possibilities for life at Venus and Mars.

VENUS

Venus is often known as our "sister planet," since it orbits the Sun just slightly inside the orbit of Earth (0.70 AU versus 1.00 AU), and has an average diameter almost the same as Earth (12,104 km versus 12,756 km). With the rapid improvements in the resolution of telescopes after its invention in the seventeenth century, it soon became possible to search for surface features on the nearby planets, and thereby signs of life. Since Venus passes closer to Earth than any other planet, Venus provided an ideal opportunity for such telescopic observations. However, these observations proved to be disappointing. As early as 1660 Christian Huygens (3) found that Venus was covered with a dense layer of clouds that completely obscured the surface. A typical ground- based telescopic image of Venus is shown in Figure 2. Although no surface features could be seen, the existence of a dense cloud cover together with its closer proximity to the Sun suggested that Venus might have an abundance of water, with warm wet conditions similar to Earth's equatorial regions, and thereby possibly teeming with life. A sketch of a possible swamp creature at Venus is shown in Figure 3, from "The Real Book About Space Travel" by Goodwin (4). This book was published just five years before the beginning of the space age, which began in 1957 with the launch of Sputnik 1.

The first hint that something might be wrong with the warm-wet picture of Venus came when Mayer et al. (5, 6) made the first ground-based microwave measurements of thermal radiation from Venus. These measurements indicated a surface temperature of ~600°K. Since microwave radiation can penetrate through the clouds, measurements of the temperature at microwave wavelengths are more nearly

FIG. 2. An amateur ground-based telescopic image of Venus, with a resolution similar to what was available to Galileo. The illuminated crescent shows that the orbit of Venus is inside the orbit of Earth, as predicted by Copernicus. [Credit: NASA]

indicative of the surface temperature than measurements at optical wavelengths, which are indicative of cloud top temperatures. These measurements prompted Sagan (7), and later Pollack and Sagan (8), as well as others, to suggest that the high surface temperature might be due to a greenhouse effect in Venus' atmosphere. However, these ideas were largely ignored, partly due to a general mistrust of the new microwave measurement technique. This all changed in 1967 when the Soviet Union began sending a series of spacecraft probes into the atmosphere of Venus. Over the period from 1967 to 1982 a total of six probes, Veneras 7 through 12, succeeded in reaching the surface (9, 10). Their measurements revealed that Venus has a dense carbon dioxide atmosphere with a surface pressure of 95 bars (1 bar $\sim$ surface pressure of Earth's atmosphere), and a surface temperature of 740°K

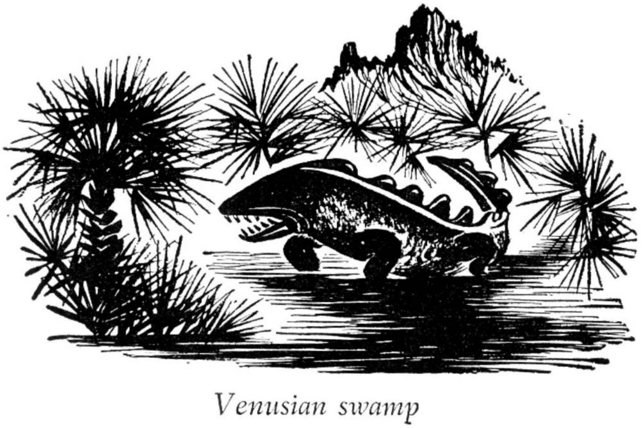

FIG. 3. An artist conception of an alligator-like creature in a Venus swamp. From Goodwin (4).

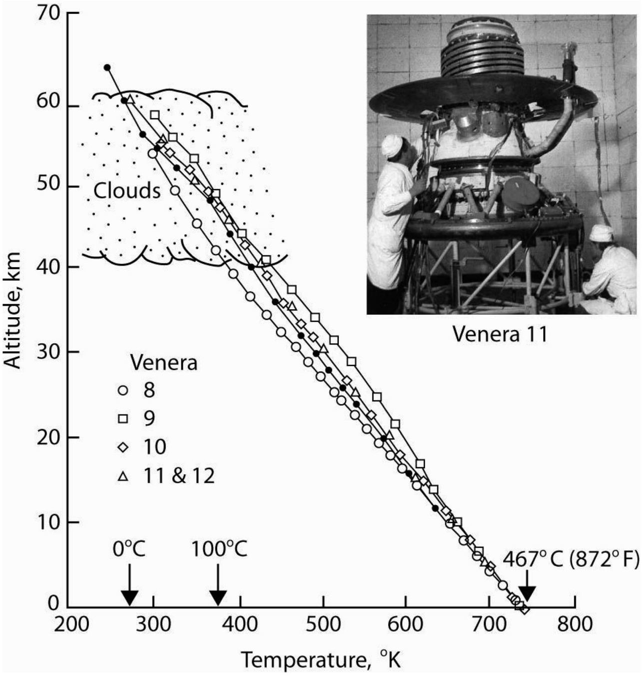

FIG. 4. Temperature profiles of Venus' atmosphere as obtained from the Soviet Venera probes, and a picture of one of the probes. Adapted from Seiff (10).

(872°F), above the melting point of lead. The measured temperatures are shown as a function of altitude in Figure 4. These astonishingly high temperatures dashed any hope of life existing at Venus. Worst than that, the small amount of water vapor that exists in the clouds was found to be in the form of sulfuric acid droplets. Pictures taken from the surface of Venus showed extensive evidence of volcanism, which probably accounts for the sulfuric acid clouds. Volcanoes at Earth are copious sources of sulfur.

It is now widely recognized that the high surface temperature at Venus, much higher than the predicted black body temperature (see Figure 1), is a greenhouse effect caused by the dense carbon dioxide atmosphere. The greenhouse effect in a planetary atmosphere, named after the trapping of heat from the light entering the glass windows of a greenhouse, is caused by the trapping of infrared radiation from the surface by an overlying layer of greenhouse gases. Water vapor, H_2O, carbon dioxide, CO_2, and methane, CH_4, are some common greenhouse gases. The basic process is illustrated in Figure 5. Sunlight energy passes through the greenhouse gases, which are relatively transparent at optical wavelengths, and heats the surface. The surface then radiates at infrared wavelengths. If a sufficient concentration of greenhouse gases is present, the infrared radiation cannot pass through the atmosphere, and is trapped between the overlaying atmosphere and the surface, thereby raising the temperature of the surface. Equilibrium is reached when the energy from the infrared radiation escaping from the top of the atmosphere, which is considerably colder than the surface, balances the incoming energy from the sunlight. The situation

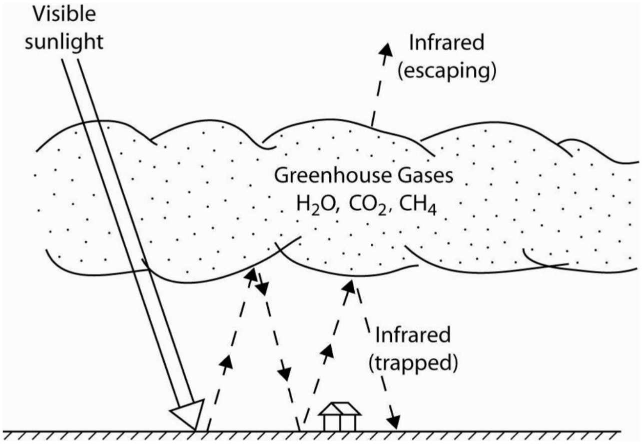

FIG. 5. Explanation of the greenhouse effect in a planetary atmosphere.

at Venus should convince everyone that the greenhouse effect is real and should not be ignored when considering the effect that burning fossil fuels may have on the future evolution of Earth's atmosphere.

So why is it that Venus, our sister planet, has evolved so differently than Earth? It is a fact that Earth has almost the same amount of carbon dioxide as Venus. The difference is that at Earth the carbon dioxide has been dissolved in the ocean and precipitated out in the form of limestone (coral reefs also play a role in sequestering carbon dioxide). So the difference is that Earth had an ocean, whereas Venus apparently did not have an ocean. In fact, it has almost no water vapor left at all. The exact reasons why Venus and Earth took such different evolutionary paths are not completely known, but the current thinking is that it had to do with the slightly higher temperature at Venus, which is closer to the Sun. It is well known that the vapor pressure of water is very temperature sensitive; liquid water evaporates very rapidly as the temperature increases above freezing. Because of the somewhat higher temperature at Venus, most of the water may have ended up as vapor in the atmosphere in the early stages of its formation, rather than liquid water in an ocean as at Earth. Over time, the water vapor in the atmosphere would then have been disassociated into hydrogen and oxygen by exposure to solar ultraviolet radiation high in the atmosphere. Hydrogen, being a very light molecule, would then have escaped to space, ultimately leaving almost no water at Venus. At Earth the comparable process did not occur, because most of the water was in liquid form and, therefore, not exposed to this disassociation and loss process. If temperature is the crucial controlling parameter, it is interesting to consider just how much closer Earth could have been to the Sun when Earth was born before it would have taken the same evolutionary path as Venus. Nobody knows. However, it is clear that the sunward boundary of the habitable zone is closer to Earth's orbit than shown in Figure 1, probably much closer.

MARS

In contrast to Venus, early ground-based telescopic images of Mars clearly showed surface features, despite the fact that it is only about half the size of Venus and at closest approach is somewhat farther from Earth (0.52 AU versus 0.3 AU). An image of Mars, comparable to those available in the latter part of the nineteenth century is shown in Figure 6. Such images showed that Mars had large reddish-orange areas, reminiscent of sandy deserts, and white polar ice caps, much like on Earth. In addition, there were large dark, slightly greenish,

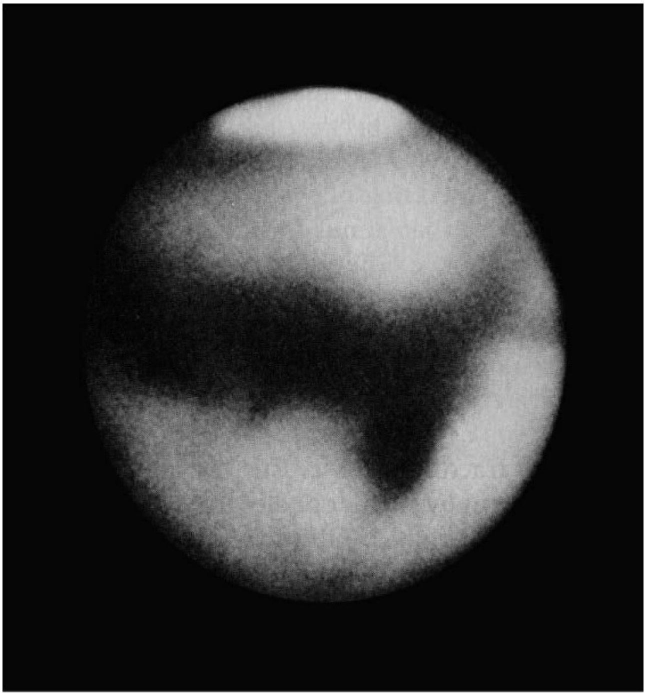

FIG. 6. A ground-based telescopic image of Mars similar to those available in the nineteenth century. [Courtesy of Lick Observatory]

areas that rotated with the planet. The rotation rate was found to be 24h 37m and its equator was found to be tilted about 25° relative to the ecliptic plane, both remarkably similar to Earth. Many observers noted that the size and shape of the dark greenish areas varied with the seasons on Mars, suggesting that the dark areas were due to vegetation. In 1877 Giovanni Schiaparelli (1835–1910), an Italian astronomer who was regarded as the foremost Mars mapper of the nineteenth century, reported seeing a series of linear features that he called "canali" connecting some of the dark areas. A sketch that he made showing some of these linear features is given in Figure 7. When his observations were reported in the U.S. press, the word "canali," which means channels in Italian, was translated as "canals," which carried the connotation that they were constructed by intelligent beings.

Schiaparelli's report of "canals" on Mars soon caught the attention of a Boston aristocrat, Percival Lowell (1855–1916) who, although not professionally trained as an astronomer, had a long interest in astronomy, especially Mars. Apparently convinced that Mars was inhabited by intelligent beings, Lowell shortly committed his considerable talent

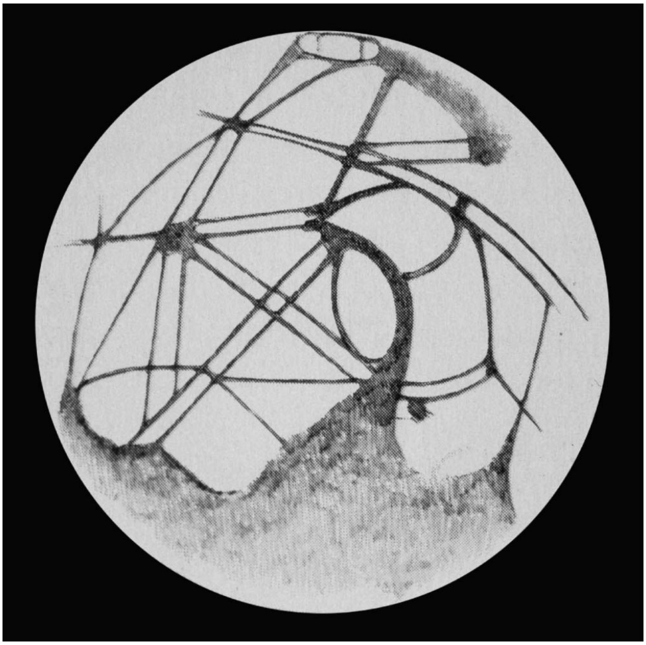

FIG. 7. Schiaparelli's 1888 sketch of Mars showing linear features that he named canali, which meant channels in Italian, but was translated as "canals" by the U.S. press.

and wealth to the construction of a state-of-the-art astronomical observatory in Flagstaff, Arizona. The observatory, now known as the "Lowell Observatory" was completed in 1894 and is still there today. Lowell devoted the rest of his life to the study of Mars. He not only confirmed the existence of the canals, but also published very elaborate sketches (11), one of which is shown in Figure 8. Lowell was a popular lecturer and developed an interpretation in which the inhabitants, soon called Martians, were using the canals to transport water from the polar ice caps to the desert areas for purposes of irrigation. To confirm that water could exist on the surface, he made measurements of the spectrum of reflected sunlight and determined that the atmospheric pressure was 85 millibars, sufficiently high for liquid water to exit. This value was later confirmed by De Vaucouleurs (12) who obtained a pressure of 85 ± 4 millibars. Lowell's ideas were so widely accepted by the public that in 1907 the *Wall Street Journal,* not know for wild speculation, stated that the most important event of the year was "the proof by astronomical observations . . . that conscious, intelligent life exists on the planet Mars." Despite the fact that other notable astronomers at the time did not see the canals, the idea that

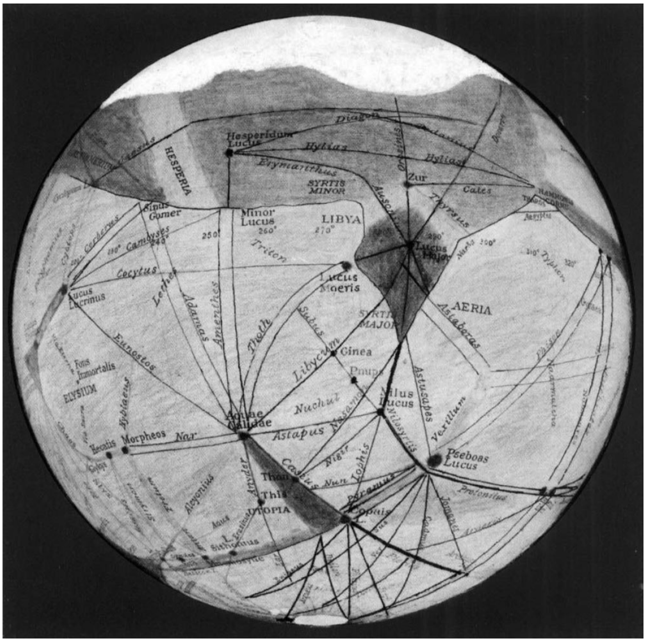

FIG. 8. Lowell's 1905 sketch of the Martian canals. From Lowell (11).

intelligent beings inhabited Mars became so widespread that in 1938 when Orson Wells and some actors read a dramatized version of H.G. Wells' book "War of the World" over the radio, it caused widespread panic on the east coast of the U.S. when they reported that a spaceship carrying Martians had landed in New Jersey.

Although by the 1950s most scientists believed that the canals were a figment of Lowell's imagination and that it was unlikely that intelligent life was present on Mars, there was a general acceptance that the dark-greenish areas were caused by plant life. An artist sketch of cactus-like plants growing at Mars is shown in Figure 9 from the "Real Book About Space Travel" by Goodwin (4) in 1952. This view was given strong support by infrared spectrum measurements of the dark-greenish area on Mars made by Sinton (13) in 1957 that were reported in the prestigious *Astrophysical Journal* as having "an almost perfect match to the spectrums of moss, lichen, and dry leaves on Earth." Sinton concluded that it is "extremely probable that vegetation in some form is present on Mars." Although the exploration of Mars via spacecraft was a high priority of both the United States and the Soviet Union, it took several years after the launch of Sputnik 1 in 1957 before it was possible to carry out a mission to Mars. The first mission to success-

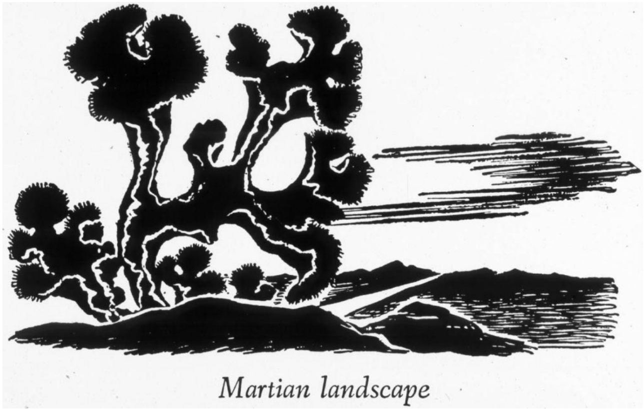

FIG. 9. An artist conception of cactus-like plants growing on Mars. From Goodwin (4).

fully reach Mars was the NASA Mariner 4 spacecraft, which arrived at Mars on July 14, 1965. A photograph of Mariner 4 is shown in Figure 10. The results from this first flyby were startling. The first close up images, shown in Figure 11, revealed a barren heavily cratered planet that closely resembled Earth's moon. Worse than that, radio occultation measurements designed to determine the atmospheric density showed that the atmosphere consisted almost entirely of carbon dioxide with a surface pressure of only 5 to 7 millibars, more than a factor of ten smaller than the 85 ± 4 millibars reported by De Vaucouleurs, too low for liquid water to exist. If a pan of water were placed on the surface of Mars the water would boil until it was all gone.

Two subsequent flyby missions, Mariners 6 and 7, which carried infrared instruments to measure the surface temperature, showed that the average temperature was very cold, about −60°C, very close to the black body temperature predicted in Figure 1. At the equator on a warm summer day the temperature just barely reaches 0° C, the melting point of water ice. During the night the temperature often falls below −100°C, and during winter in the polar regions sometimes below −128°C, the freezing point of carbon dioxide. Since the atmospheric composition is almost entirely carbon dioxide, this very low temperature raised the possibility that the polar ice caps were made up of carbon dioxide ice rather than water ice. This possibility was soon confirmed by infrared spectrum measurements from Mariners 6 and 7, which showed that the surface of the ice caps was carbon dioxide. Later missions were to show that the polar ice caps are, in fact, mainly water ice, but that a thin layer of carbon dioxide frost forms over the polar cap during the Martian winter.

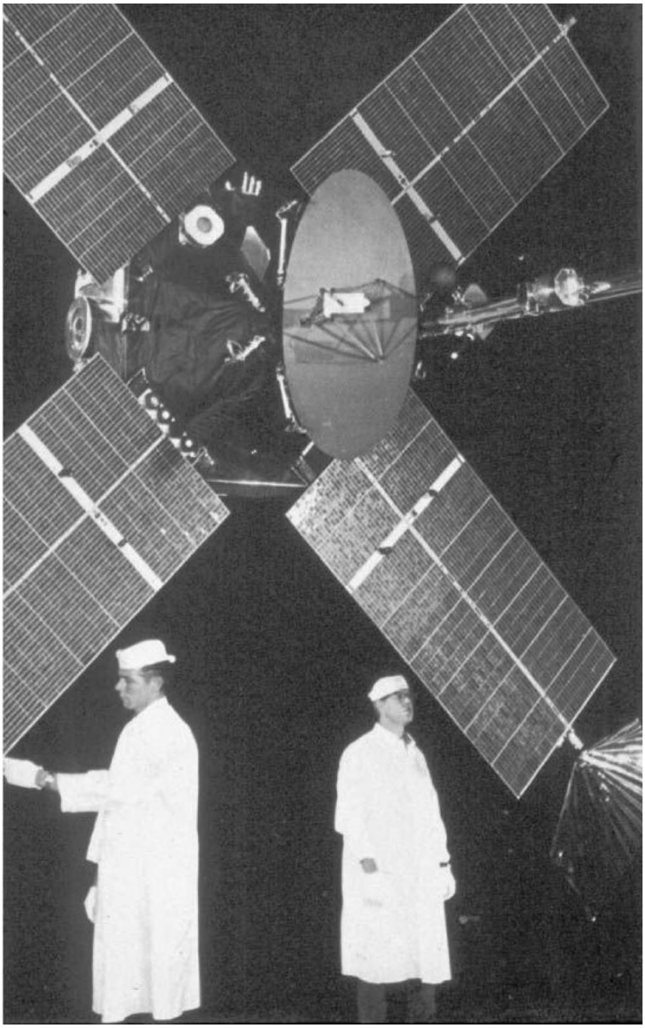

FIG. 10. Mariner 4, the first spacecraft to successfully fly by Mars. [Credit: NASA/JPL]

Although Mariners 4, 6 and 7 appeared to have effectively dashed any hope that life might exist at Mars, the next mission to Mars, Mariner 9, revealed a somewhat more encouraging picture. This spacecraft was the first spacecraft to be placed in orbit around Mars and arrived on Nov. 13, 1971. Since it was in orbit, it was able to take many more images with much better coverage than was available from the brief Mariner 4, 6 and 7 flybys. These images showed many new

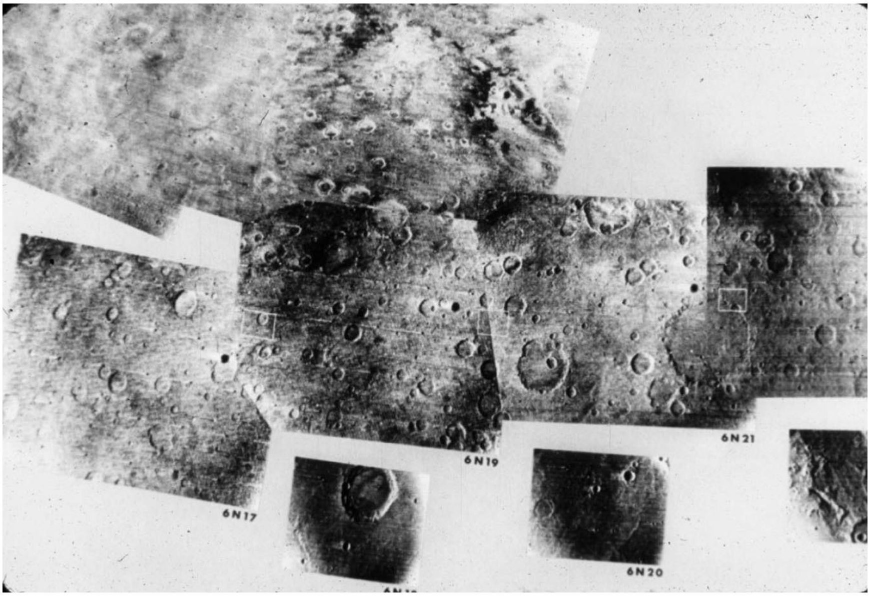

FIG. 11. A collection of the first close up pictures of Mars from Mariner 4. [Credit: NASA/JPL]

features, such as extinct volcanoes, deep canyons and, most surprising of all, dry river beds with tributaries. Some of the dry riverbeds had teardrop-shaped erosion features, such as shown in Figure 12. These

FIG. 12. An image of two tear-drop shaped erosion features in a dry river bed at Mars. Such features can only be caused by large amounts of flowing water. [Credit: NASA/JPL]

erosion features provided convincing evidence that Mars once had substantial amounts of flowing water. No other naturally occurring fluid is known that could have produced these teardrop features. The presence of dry river beds showed that the atmospheric pressure and temperature must have been considerably higher sometime in the distant past, and therefore more favorable for life. Just how long ago is hard to say, but most estimates place this more temperate era several billion years ago. This was encouraging for those searching for evidence of life, since if advanced life once existed, there might still be fossils that some day could be found. Also, since Mars once had water, it is almost certainly still there. Mars is now clearly in an ice age, so the water would have to be in the form of ice. There are two possibilities where the water ice might be located: (i) in the polar ice caps, and/or (ii) underground in the form of permafrost. Either way, since water provides one of the essential ingredients for life, the situation is clearly better than implied by the first images from Mariner 4, which suggested that Mars was completely barren and dry, like Earth's moon. At Earth microbial life is known to be able to survive in extremely cold conditions in the presence of water ice, such as in the Antarctic ([14]). So even though conditions at Mars are not favorable for advance life, the thinking at the time was that the surface conditions might be favorable for microbial life.

Based on the hope that microbial life might be present on the surface, an ambitious mission was undertaken by NASA in the mid-1970s to search for microbial life. The mission consisted of two spacecraft, Vikings 1 and 2. Each spacecraft consisted of two parts, a mother ship, the "Orbiter," which was put into orbit around Mars, and a "Lander," which descended to the surface. A picture of one of the Landers is shown in Figure 13 A replica of a Viking Lander can be seen at the Smithsonian Air and Space Museum in Washington, DC. Landing on Mars is very difficult. The atmosphere is too thin for a direct parachute descent, so retro-rockets must be used to carry out the landing. Also, the landing sequence must be completely automatic, since the time for a radio signal to reach Earth is too long, typically several minutes, to allow real-time control from Earth. Despite these difficulties, both Landers successfully touched down on Mars, the first on July 20, 1976, and the second on Sept. 3, 1976. The Landers each had a scoop on the end of an extendable arm to pick up and deliver samples of the Martian soil to a chemical analysis system. A gas chromatograph-mass spectrometer (GCMS) was used to test for organic molecules, and three highly specialized instruments were used to detect the metabolic activity of any microorganisms that might be

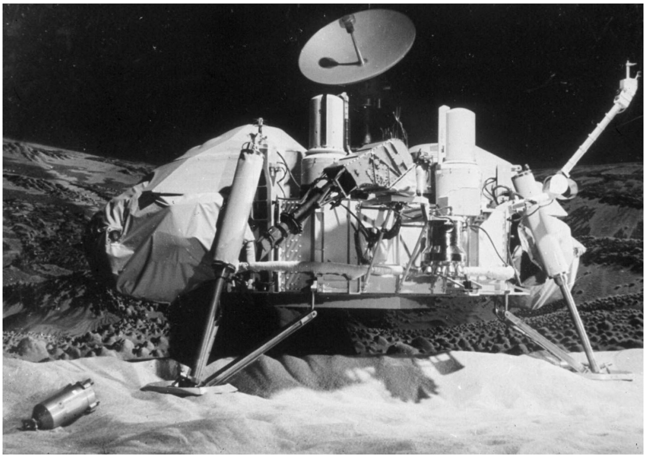

FIG. 13. One of the two Viking Landers. [Credit: NASA/JPL]

present. A full description of these instruments can be found in Horowitz (15). The GCMS was extremely sensitive and could detect organic compounds with a sensitivity ranging from a few parts per billion to a few parts per million, depending on the molecular mass. No organic material was detected at either landing site. Since the dusty surface material is likely to be distributed globally by the high winds that sometimes occur at Mars, the complete absence of organic material is generally believed to be characteristic of the entire planetary surface (15). This is in sharp contrast to Earth, where organic material is present in soil samples taken almost anywhere, even in extreme climates, such as in the Antarctic. Although there were initially some unusual and unexpected responses from the metabolic instruments, in the end it was concluded that no metabolic activity was present in the soil samples at either landing site. However, in the process of explaining the unusual responses, it was discovered that the soil contained significant levels of oxygen-rich peroxides. The peroxides, which are highly toxic to living organisms, are believed to be produced by chemical interactions induced by the intense solar ultra-violet radiation incident on the surface of Mars. In contrast to Earth, where ozone in the upper atmosphere shields us from such radiation, at Mars there is no comparable shielding due to the very thin atmosphere and the almost complete absence of oxygen.

As a result of the Viking 1 and 2 failures to detect signs of life, the focus of Mars explorations has changed significantly in recent years. Although several very successful spacecraft and rover missions have recently been sent to Mars, no further experiments have been per-formed specifically to search for life. The focus now is on understanding the geology of Mars and finding out where the water went. Various remote sensing instruments have shown that large areas of permafrost are present at Mars (16). Although the surface is believed to be inhospitable to life, it is possible that microbial life could exist deep under the surface, provided there is liquid water and a suitable source of energy. Since radioactive heating is expected to raise the temperature of the interior, it is believed that a layer of liquid water might exist under the permafrost. To search for such a layer of liquid water, a low-frequency surface-penetrating radar was flown to Mars in 2003 aboard the European Mars Express spacecraft. My group at Iowa played a major role in designing and building this radar. An artist sketch of the spacecraft and its radar antenna is shown in Figure 14. Although no sub-surface liquid water has yet been found, the radar for the first time was able to measure the thickness of the southern polar ice cap. The thickness was found to be 3.7 km (17). This is a very thick ice cap, comparable to the ice caps that covered Earth's polar region during the last ice age. If melted, the water in the polar ice caps would cover the planet in a layer over 20 m deep. An even larger amount of

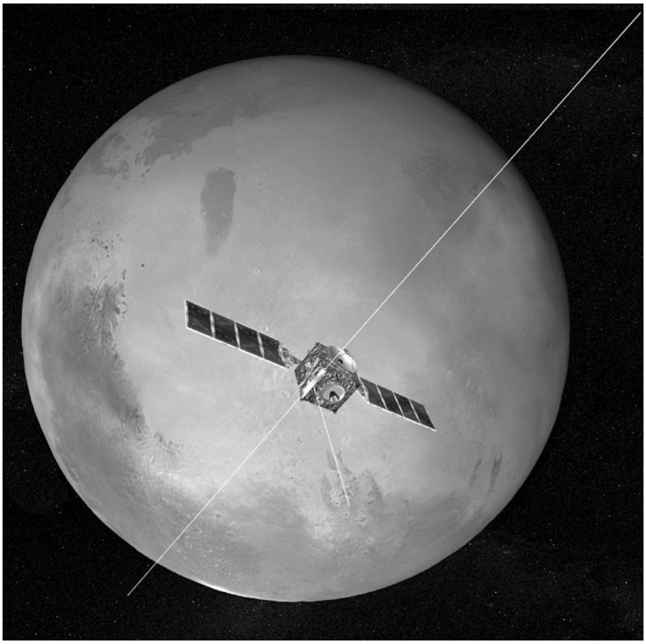

FIG. 14. The European Space Agency Mars Express spacecraft orbiting Mars. This spacecraft carries a low-frequency radar designed to search for sub-surface water. The long antenna is part of that radar system. [Credit: ESA/NASA/JPL]

water is probably present in the form of permafrost elsewhere on the planet. Whether suitable sub-surface conditions will ever be found that can support life in or below the permafrost is yet to be answered and is still one of the goals of current day research at Mars.

MOONS OF THE GIANT PLANETS

Inspection of the blackbody temperatures in Figure 1 suggests that the planets beyond the orbit of Mars, specifically Jupiter, Saturn, Uranus, and Neptune, would be unlikely to support life, since the temperatures are extremely cold. These giant planets are not only extremely cold, but are totally different than Earth. They are big balls of gas and have no solid surface, more like the Sun than the terrestrial planets, Mercury, Venus, Earth, and Mars, all of which have solid rocky surfaces. Although these gas giants do not appear to have conditions suitable for life, it has just recently been realized that the interiors of some of the moons of these planets may have conditions suitable for life. There are two reasons why these moons are of interest. The first is that these moons tend to have a considerable amount of water, in the form of water ice. Water ice is common in the very cold outer regions of the solar system, apparently because water was a common material in the solar nebula that collapsed to form all the planets and moons. Once it freezes onto a surface in these very cold conditions it remains solid, like rock at Earth. The second is that many of these moons also have condensed hydrocarbons and organic material on their surfaces. The textbook case is Saturn's moon Titan. During the first flyby of this moon by Voyager 1 in 1980, it was discovered that hydrocarbons and organic molecules are present in its atmosphere ([18–20]). It is believed that this material was either present in the solar nebula from which the planets and moons were formed, or was brought to the moons by comet impacts. Comets are known to have hydrocarbon and organic molecules ([21, 22]). Thus, water and organic material, two of the most essential ingredients for life, are present on many, if not most, of these moons. The problem with respect to the possible presence of life is their very low temperatures. However, we now know that there is a mechanism for substantially raising the interior temperature of some of these moons, namely tidal heating. The classic example of tidal heating is at Io, the innermost of the four Galilean satellites. Io is a completely rocky moon with no outer ice covering. During the first Voyager 1 flyby of this moon in 1979 it was discovered ([23]) that Io is highly volcanic, the only object in the solar system other than Earth that has active volcanism. This volcanism is driven by internal heating due to tidal forces caused by Jupiter and other nearby moons.

There are now known to be at least two ice covered moons in the outer solar system that have sufficient tidal heating to raise their interior temperatures above the melting point of water. They are Europa, which is the second of the Galilean satellites at Jupiter, and Enceladus, which is one of the inner moons at Saturn. Europa has an average density that is consistent with a rocky interior, but is covered with a thick layer of water ice. The ice covering has an extensive network of cracks, often with dark upwelling material in the cracks. These cracks can be easily seen in Figure 15, which is an image of Europa taken by the Voyager 1 spacecraft (23) in 1979. These cracks led some to suggest that the ice may overlie a liquid water ocean that is kept warm by tidal heating. This view was given much stronger support by high resolution images taken by the Galileo spacecraft (24) in 1996–1997 that showed what appeared to be "ice rafts," broken floating pieces of ice that have separated, like the pieces of a jigsaw puzzle. A Galileo image showing these ice rafts is shown in Figure 16. The dark material between the ice rafts is not liquid water, but refrozen

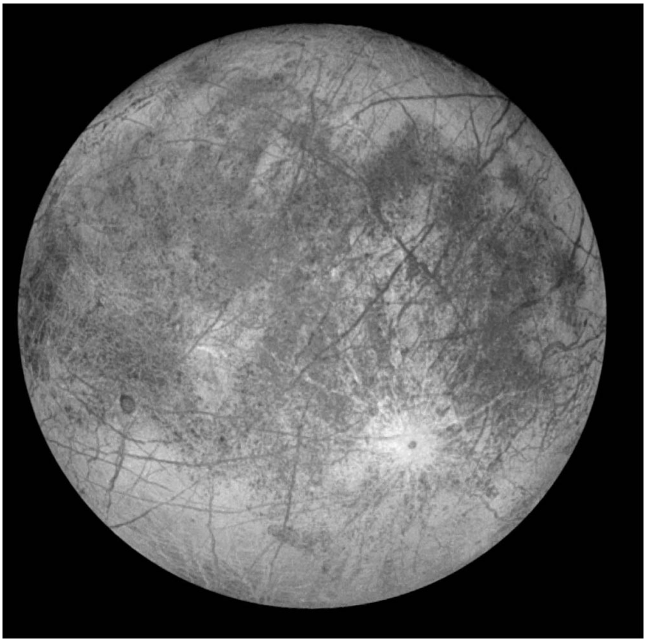

FIG. 15. Jupiter's moon Europa, as imaged by the Voyager 1. Numerous cracks can be seen in the thick covering of water ice on this otherwise rocky moon. [Credit: NASA/JPL]

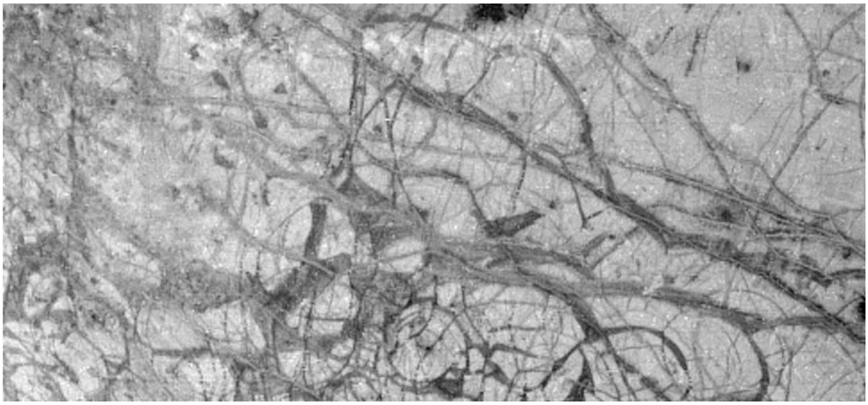

FIG. 16. A close up image of Europa showing what appears to be isolated “ice rafts,” such as formed at Earth when ice breaks up on a large body of water. These ice rafts and the extensive cracks evident in Figure 15 suggest that the ice is floating on an underlying ocean of liquid water. [Credit: NASA/JPL]

water discolored by some unknown dark material. Because of the very low level of solar heating, any water that flows up between the cracks quickly freezes due to the radiated heat loss. This and other evidence have convinced many scientists that an ocean of liquid water lies under the ice covering at Europa. For a discussion of the various arguments for, and against, this conclusion see Squyres (25) and Pappalardo et al. (26).

The likelihood that Europa has a liquid water ocean under the ice opens up some entirely new possibilities in the search for life. Several researchers have suggested that the conditions in such an ocean might be ideal for life to originate and evolve (27–29), even though there is almost no energy available from sunlight. This possibility is given further support by the recent suggestions that life on Earth may have arisen near hydrothermal vents at the bottom of the ocean (30). Complete ecosystems have been found to flourish around such vents, which obtain their energy not from sunlight, but rather from gaseous hydrogen sulfide escaping through the vents. Since tidal heating in the rocky interior of Europa provides a heat source comparable to radioactive heating in Earth’s interior, it is believed that similar hydrothermal vents, possibly surrounded by living things, may exist at the bottom of Europa’s ocean.

An even more impressive example of an icy moon with interior conditions possibly suitable for life has been recently been found at Saturn’s moon, Enceladus. During the first flyby of this moon by the Voyager 1 spacecraft in 1980, it was noted that impact craters were entirely absent in a large area of the moon, suggesting that the surface was being altered by some internal heat source, such as tidal heating. More recently, images from the Cassini spacecraft, which was placed in orbit around Saturn in 2004, revealed several long parallel fissures near the southern polar region. These features can be seen in Figure 17, which is one of the early close-up images of Enceladus taken by Cassini. At about the same time other instruments on Cassini detected evidence of gaseous material coming from the southern hemisphere of the moon (31). Based on this evidence the spacecraft was maneuvered to take a series of images from the dark-side of Enceladus, looking toward the Sun, in order to detect any material escaping from the moon in the forward scattered light. These images confirmed the presence of a geyser- like plume of material ejected from the fissures in the southern hemisphere (32), see Figure 18. To determine the chemical composition of the plume, the spacecraft was later maneuvered to

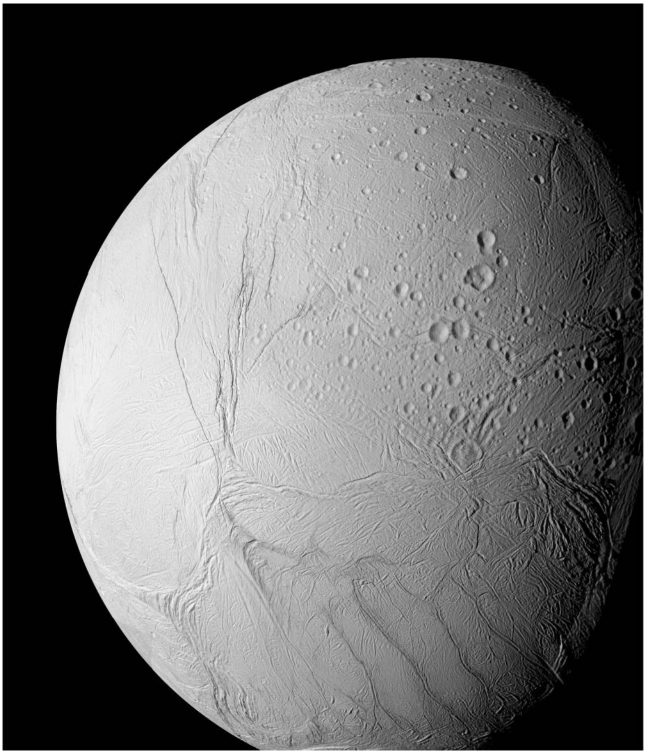

FIG. 17. Saturn's moon Enceladus, as imaged by the Cassini spacecraft. Note the pronounced parallel fissures in the southern (lower) portion of the moon. [Credit: NASA/JPL]

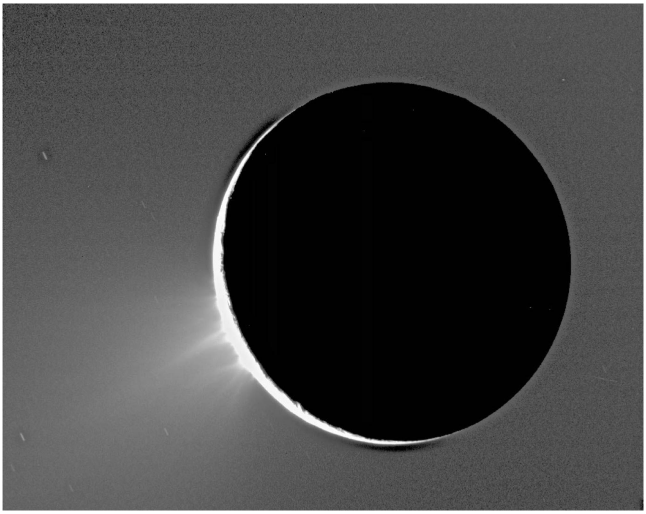

FIG. 18. An image of Enceladus taken by Cassini with the Sun behind the moon. The feature protruding out of the lower left side of the moon is a geyser-like plume of water and organic material ejected from the fissures evident in Figure 17. [Credit: NASA/JPL]

make a pass directly through the plume. This was accomplished on March 12, 2008. A mass spectrometer on the spacecraft confirmed that the primary composition of the plume was water vapor. Amazingly, it also revealed the presence of numerous hydrocarbons and organic molecules. A mass spectrum of the material in the plume is shown in Figure 19. Some of the compounds identified include acetylene, C_2H_2, ethane, C_2H_6, hydrogen cyanide, HCN, and formaldehyde, H_2CO. This discovery of liquid water ejected from this moon represents an important landmark in the search for life in the solar system. Enceladus is now the only object in the solar system other than Earth that is definitely known to have liquid water.

CONCLUSION

In this presentation I have chronicled the long struggle to answer the basic question, does life exist anywhere else in the solar system? A century ago there were learned people who thought that there was most likely life, maybe even intelligent life, at our nearby planets Venus and Mars. The space age exploration of the planets has radically altered that view. Venus is now known to be extremely hostile to life, with a surface temperature above the melting point of lead, and almost completely devoid of water. Mars appears to be almost completely barren and in an ice age, with surface conditions that are hostile to life.

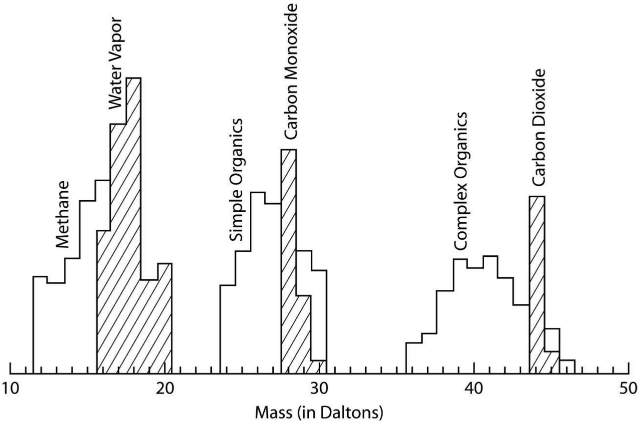

FIG. 19. The mass spectrum of material detected in the Enceladus geyser plume during a Cassini passage through the plume on March 12, 2008. [Credit: NASA/JPL/SwRI/SSI presented at NASA Press Conference, March 26, 2008.]

These very sobering findings are, I believe, the most important scientific results of the space age. They show that Earth, with its moderate temperatures and abundant water, is indeed a very special place.

Life may still exist somewhere else in the solar system, but the possible places where it might be found are now getting very restrictive. It is going to be difficult to explore the remaining possibilities. Because of the inhospitable conditions on the surface, if life currently exists at Mars it would have to be in the form of microbial life deep under the surface. This will require drilling into the interior to search for life. It is possible that in the distant past, a billion or more years ago, when water once flowed on Mars, conditions may have been more hospitable. If life existed then, it might be possible to find fossil evidence of this life. For these and other reasons NASA is continuing to pursue an active program of Mars exploration, including both robotic and eventually human missions to Mars. Whether this effort will ever discover life, or evidence of past life remains to be seen.

The recent unexpected discovery of liquid water in the interior of Enceladus and the possibility that a liquid water ocean may exist under the ice at Europa opens up an entirely new arena in the search for life. Given the large number of icy moons orbiting the giant outer planets, and the tidal forces that exist between the planet and these moons, it may well be that some of the other moons have liquid water oceans under their ice covering. The icy moons, Ganymede and Callisto, at Jupiter are realistic possibilities. To search for life in the interior of these moons is going to be difficult. The basic approach being discussed is to put a robotic submarine down under the ice to search for hydrothermal vents and associated life. Before that can be done we need to know the thickness of the ice. If it is a hundred meters thick it is possible, but if it is ten kilometers thick, probably not. The next step, which is currently being planned, is to send an orbiter to Europa with a low-frequency surface-penetrating radar, similar to the Mars Express radar (see Figure 14). The objective will be to measure the thickness of the ice and select the best location to insert a submarine. My group at the University of Iowa is designing a high power radar transmitter for use on this project. Stay tuned for future developments.

ACKNOWLEDGEMENTS

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