LIFE AS A PLANETARY PHENOMENON

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Abstract. The success of recent spacecraft from the U.S.A. and the U.S.S.R. has given us a wealth of new data about the planets in our solar system. We can now develop a much better rationale for the reasons that abundant life is only found on our planet. Mars, smaller and more distant from the Sun, may nevertheless hold clues to the early development of Earth's atmosphere. The origin of life on Mars early in that planet's history cannot be ruled out. Titan offers a contemporary example of extremely primitive conditions, where chemical reactions resembling those that preceded the development of life on Earth may be occurring today. Venus and Jupiter illustrate the need for a planet to be the right size and the right distance from the sun if chemical evolution leading to the origin of life is to occur.

1. Introduction

Our perspective about our home planet has undergone many changes over the course of recorded history. While some early philosophers felt that the Earth was only one of many similar worlds, the view of Claudius Ptolemaeus, who lived in the 2nd century A.D., struck a special response in the Western mind. Ptolemy set the Earth at the center of the universe, with the sun, moon, planets and stars all moving around it. This conception of the uniqueness of our planet is not unlike the feeling of the infant who comes into the world as the center of attention. But just as the growing child discovers there are other children, other adults, even other cities and countries, astronomers realized with time that the Earth actually moves around the sun, that our sun is a common type of star, occupying no special position in the galaxy, and that our galaxy is just one of billions of similar systems of gas, dust and stars.

All this would seem to suggest that there is nothing very special about the Earth. But among the planets we know, the Earth is in fact strikingly unique: it is the only world in our solar system on which abundant life exists. Why is this so? How likely is it that this strange subtle property of matter – being alive – could exist on some other planet in some other solar system? Is it possible that the properties that have led to the existence of life on Earth are so special and extraordinary that we are alone in the universe, the only thinking beings pondering such riddles?

The answers to these questions can be sought in different ways. The approach I shall take is to compare the Earth with the other planets in our solar system, to try to understand the reasons why Earth differs from its neighbors and to see what the other planets can tell us about the early history of the Earth, when life actually originated on our planet. The focus of this comparison will be on planetary atmospheres, since it is clear that our atmosphere has been vital both to life's origin and to its preservation.

Ten years ago, this would have been a very difficult task to accomplish in any detail. But during the last decade, all but three of the planets in our solar system have changed from being little more than points of light in the sky, which we studied with the large

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telescopes and spectrographs at our major observatories, to familiar worlds that have been visited by spacecraft. These missions and the concurrent improvements in conventional methods of Earth-based observation have brought us much new information that is relevant to this study. In the course of our review of these new data, we will discover worlds whose early histories may have closely resembled the early history of our own planet, and others on which current conditions offer present-day parallels to those primitive times on Earth when atmospheric chemistry led to the development of life. Thus our fellow planets can serve as natural laboratories in which we can test our ideas about the origins of atmospheres and the origin of life itself.

2. The Importance of Planetary Atmospheres for Life

We may seem to be making many implicit assumptions by suggesting that planets with atmospheres are a necessary precondition for the existence of life. We may be accused of being chauvinistic, influenced too greatly by the conditions in which we find ourselves on Earth. But we now know much about many more worlds than ours and it is hard to conceive of life existing on any planet without an atmosphere. Our experience in exploring the Moon, with no atmosphere, and Mars with a very tenuous atmosphere, bears out this preconception. On neither body could we find any evidence of organic compounds, even disregarding living organisms.

We are all familiar with the many ways our atmosphere protects us and keeps us alive. Beginning with the oxygen that is essential to our existence, we can add the transport of water vapor and carbon dioxide, the global warming produced by infrared radiation trapped by these same two gases, the ozone shielding us from harmful ultraviolet light, the modulation of the daily temperature cycle, and of course the high pressure exerted at the Earth's surface, which allows water to remain in the liquid state, and permits life in all its myriad forms to use this remarkable substance for its continued existence.

At the risk of seeming somewhat narrow minded, most scientists feel that any type of life, anywhere in the universe, will depend on water as a fluid medium and carbon as the basic structural element for its chemistry. This apparent prejudice is actually based on the very special properties of these two substances. Water is a remarkable solvent, it has a high heat capacity, it is an excellent absorber of infrared radiation, it remains liquid over a wide temperature range, and this range is appropriate to a wide variety of chemical reactions. Furthermore, water is composed of two very common elements, and when it is broken apart by ultraviolet light, its oxygen becomes available as a new source of chemical energy. Carbon is also an abundant element and is unique for the wide variety of complex compounds it can form with other elements. The whole field of organic chemistry is based on this property, which is required for the production of large, intricate, information-containing molecules essential for the development of a self-replicating, evolving system that we would consider alive.

Hence the fact that we find ourselves amidst an abundance of life on a planet blessed with an abundance of water is not a simple coincidence. Strictly speaking, the water in our oceans, rivers, lakes, clouds and rainbows is really part of our atmosphere. The average temperature on Earth just happens to be in the right range for most of this gas (water vapor) to condense as a liquid. In some regions it forms a solid – glaciers, icebergs, the great polar ice caps – and everywhere a tiny fraction is present as vapor in the lower region of the atmosphere.

The carbon that is so vital to us is present mainly in the form of mineral deposits (the carbonate rocks such as the White Cliffs of Dover), in deposits of organic matter that was once alive (coal, petroleum), in living organisms (from viroids to viceroys), and in a tiny amount of methane and a larger quantity of carbon dioxide in the atmosphere. An inventory of these and other atmospheric constituents is given in Table 1. How did these gases become the air we breathe?

TABLE I

Atmospheric composition of Earth*

		Fraction of dry air			
Gas	Molecular weight	by volume	by weight	Amount	Notes
		$\times 10^{-6}$	$\times 10^{-6}$	Atmo-cm	
N_2	28.013	780,840	755,230	624,000	
O_2	31.999	209,470	231,420	167,400	
H_2O	18.015	1000–28,000	600–17,000	800–22,000	bd
Ar	39.948	9340	12,900	7450	
CO_2	44.010	820	500	260	a
Ne	20.179	18.2	12.7	14.6	
He	4.003	5.24	0.72	4.2	
CH_4	16.043	1.8	1.0	1.4	
Kr	83.80	1.14	3.3	0.91	
CO	28.010	0.06–1	0.06–1	0.05–0.8	a
SO_2	64.06	1	2	1	a
H_2	2.016	0.5	0.04	0.4	
N_2O[3]	44.012	0.27	0.5	0.2	
O_3	47.998	0.01–0.1	0.02–0.2	0.25	bc
Xe	131.30	0.087	0.39	0.07	
NO_2	46.006	0.0005–0.02	0.0008–0.03	0.0004–0.02	a
Rn	222	$0.0^{13}6$	$0.0^{12}5$	5×10^{-14}	
NO	30.006	Trace	Trace	Trace	a

[a] Greater in industrial areas; [b] meterological or geographical variations; [c] increases in ozone layer; [d] decreases with height.

Some additional atoms or molecules may be detected spectroscopically in the night sky or aurorae

*From *Astrophys. Quant.* (Edited by Allen C. W.), 3rd Edition (1973).

3. The Origin of Atmospheres

We commonly think of two principal types of planetary atmospheres: primary and secondary. A primary atmosphere is one that consists of gases captured from the primordial solar nebula – the cloud of gas and dust from which the entire solar system originated – at the time of formation of the planet itself. We expect such an atmosphere to be rich in hydrogen and helium, as these are the most abundant elements in the universe and they remain gases at very low temperatures. Since hydrogen is roughly ten times more abundant than helium and a thousand times more abundant than anything else, we may expect to find compounds of this element dominating such atmospheres. Thus we anticipate methane (CH_4), ammonia (NH_3), water (H_2O), hydrogen sulfide (H_2S), etc. If a planet is to maintain such an atmosphere for the 4.6 billion years since it formed, it will have to be cold and massive. Otherwise, the light, fast-moving hydrogen molecules will escape.

Accordingly, in our solar system we find such atmospheres on the outer planets, far from the sun. (We expect this same situation to exist in other solar systems too; but at present we have no data to prove it!) Jupiter, Saturn, Uranus and Neptune all have atmospheres dominated by hydrogen, with methane and other hydrogen-rich compounds as the minor constituents (Table II). These atmospheres are thus very primitive; they represent conditions similar to those that existed in the primordial solar nebula 4.6 billion years ago. Furthermore, chemical evolution in such atmospheres is limited, since hydrogen is the overwhelming constituent and it cannot escape from the planet's gravitational field. Thus when molecules are broken apart by solar radiation, there is always plenty of hydrogen around with which they can recombine. Another limitation is posed by the absence of solid surfaces on these bodies: there are no places

TABLE II

The composition of outer planet atmospheres

Gas	Jupiter	Saturn	Uranus	Neptune
H_2	1	1	1	1
CH_4	$1\text{–}4 \times 10^{-3}$	10^{-3}	0.03	0.04
NH_3	2×10^{-4}	2×10^{-5}	–	–
H_2O	10^{-6}	–	–	–
C_2H_2	8×10^{-7}	1×10^{-1}	–	?
C_2H_6	4×10^{-5}	7.5×10^{-6}	–	Yes
CO	3×10^{-9}	Yes	$<2 \times 10^{-4}$	–
HCN	2×10^{-9}	$<7 \times 10^{-9}$	–	–
GeH_4	6×10^{-10}	–	–	–
PH_3	4×10^{-7}	3×10^{-6}	–	–
C_3H_4		Yes	–	–
C_3H_8	Yes	Yes	–	–

There is still considerable uncertainty about many of these values, as indicated explicitly in the range given for CH_4 on Jupiter. A 'yes' indicates identification but no abundance determination.

where pools of concentrated chemicals could form. These immensely deep atmospheres simply merge imperceptibly into fluid interiors, at very high temperatures. All except Uranus are radiating more energy than they receive from the sun. Hence compounds formed high in the atmosphere will be brought down by vertical circulation to levels where they will be destroyed by heat.

And yet, and yet ... we find evidence in the forms of tiny quantities of unexpected constituents, like carbon monoxide and hydrogen cyanide, that some non-equilibrium chemistry is occurring. The presence of colors among the clouds on Jupiter also emphasizes this point. Ammonia forms white clouds when it condenses, just like our water clouds on Earth. But on Jupiter, we see reds, browns, tawny golds and other shades, indicating that other substances are present (Figure 1). These could include

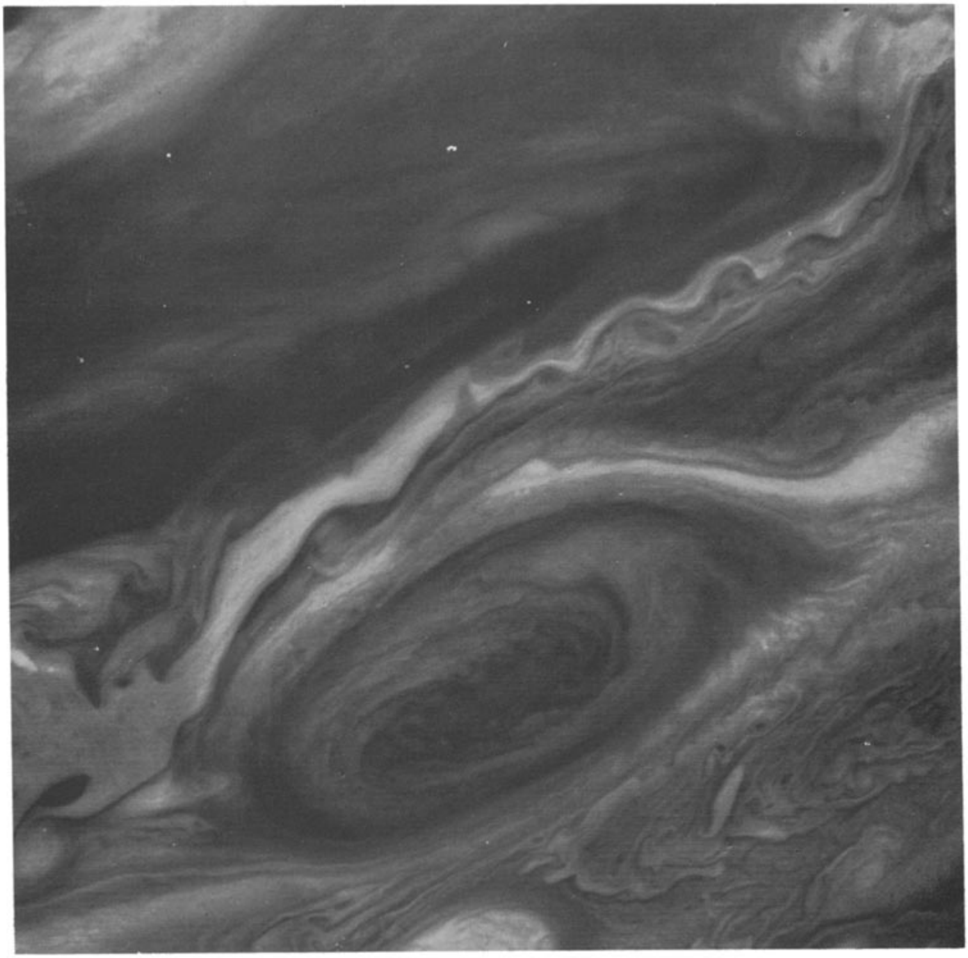

Fig. 1. The clouds of Jupiter in the vicinity of the Great Red Spot (GRS) as seen by Voyager 1 in 1979. This large oval disturbance is bigger than two Earths. Its color is caused by traces of some as yet unidentified chemicals produced in the planet's atmosphere. The smaller oval beneath the GRS is probably white because it is a place where ammonia is condensing as cirrus crystals. (JPL NASA photograph.)

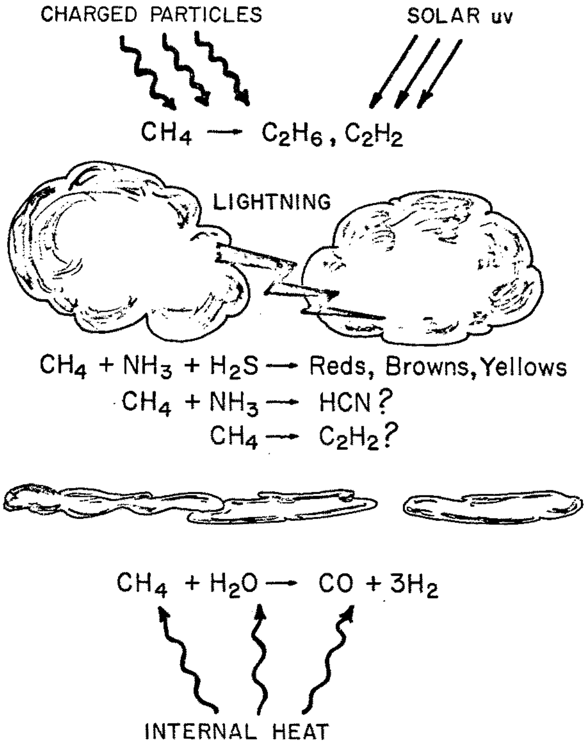

Fig. 2. A schematic diagram of known energy sources on Jupiter and some of the possible chemical reactions they may drive.

compounds of sulfur and phosphorous, carbon and nitrogen, formed by the action of solar ultraviolet light, lightning discharges in the Jovian clouds, the internal heat source that the planet possesses, or even charged particles from Jupiter's radiation belts (Figure 2). Thus some chemical evolution is occurring on this giant planet – we do not yet know to what level of complexity it has progressed.

Closer to the sun, things are different. Here the primordial nebula was hotter, and conditions were not suitable for the formation of large, hydrogen rich planets. Instead, small rocky planets developed, and these have secondary atmospheres.

A secondary atmosphere, as its name implies, is produced by the planet itself from the rocky materials of which it is composed. Heating of this material during the course of accretion of the planet or by subsequent production of energy by decay of radioactive elements drives off the gases it contains. These gases then form the atmosphere. We can gain an idea of what gases there are by studying the gases contained in meteorites and the gases presently being produced by active terrestrial volcanoes. This is not a completely reliable procedure, since meteorites cannot be assumed to be *identical* with planet-forming material and present volcanic gases may differ from those produced shortly after Earth's formation. With these caveats, we conclude that we should expect a small amount of hydrogen, and larger quantities of nitrogen, ammonia, methane, carbon monoxide, carbon dioxide and water vapor.

The subsequent fate of these gases depends on the planet's size and distance from the sun. Small bodies like the Earth will lose hydrogen rapidly. Simultaneously, compounds like methane and ammonia will be broken down by solar ultraviolet light into smaller fragments plus hydrogen; the hydrogen will escape and the resulting fragments will be oxidized as a result of the presence of water vapor, which will itself be broken apart by solar u.v.

Thus for an Earth-like planet near the sun (and this should be true in any solar system), there is an inevitable progression toward an atmosphere containing carbon dioxide, nitrogen and water vapor. And yet at the beginning it is highly likely that all such planets had atmospheres that included water, some molecular hydrogen and some hydrogen-containing compounds. As laboratory simulations have shown, the action of solar ultraviolet light, lightning, and local sources of heat on such an atmosphere leads to the production of a variety of important components for living systems. The presence of solid surfaces on such bodies permits the formation of quasi-stable micro-environments, like tide pools, in which compounds can be concentrated and further chemical reactions can occur. This is the setting commonly assumed for the origin of life on Earth. It should have existed on Mars and Venus too, shortly after these planets formed.

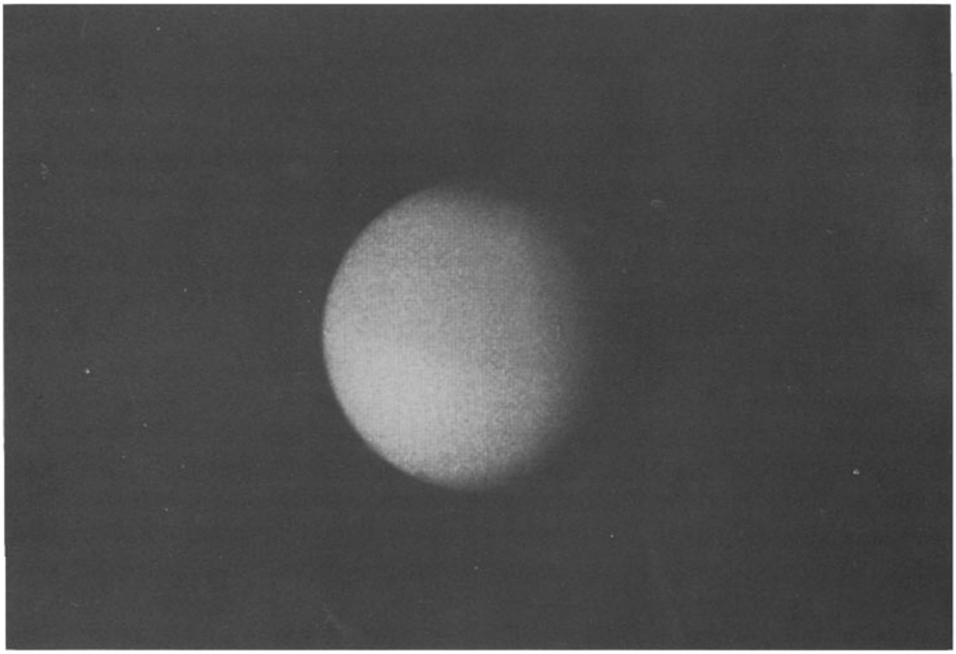

Fig. 3. Saturn's largest satellite Titan, photographed by *Voyager 1* in November 1980. The surface of the satellite is perpetually shrouded by a thick aerosol produced by photochemical reactions in Titan's atmosphere. An underlying cloud of condensed methane may also be present (see Fig. 4 and Table 3). (NASA JPL photograph).

TABLE III

The atmosphere of Titan

Major constituents	
Nitrogen (N_2)	82-99%
Argon (Ar)	0 12 (deduced from $\mu = 28.6$)
Methane (CH_4)	1 6 (varies with altitude)
Trace constituents	
Hydrogen (H_2)	2000 ppm
Acetylene (C_2H_2)	2
Ethylene (C_2H_4)	0.4
Ethane (C_2H_6)	20
Diacetylene (C_4H_2)	0.1 0.01
Methylacetylene (C_3H_4)	0.03
Propane (C_3H_8)	20
Cyanogen (C_2N_2)	0.1 0.01
Hydrogen Cyanide (HCN)	0.2
Cyanoacetylene (HC_3N)	0.1 0.01
Carbon monoxide	50 150
Carbon dioxide	0.0015

Aerosol that absorbs strongly in u.v. exhibits hemispheric change in albedo (south is brightest as northern spring begins) and shows distinct layering plus dark northern polar hood. Surface pressure is 1.5 bars, temperature is 94 K.

On the other hand, a small planet *far* from the Sun – Saturn's satellite Titan, for example–will have a very different history. Hydrogen will still escape, but oxidation will not occur because the water on such a planet is completely frozen out on its surface or interior. Thus no source of oxygen is available, and the gases will not become oxidized. A secondary atmosphere is produced by the degassing of rocks and evaporation of ices during the accretion and early history of Titan. Today we find nitrogen as the main constituent, either the result of photochemical destruction of ammonia, or because it was trapped in the ices that formed the satellite. Methane is the next most abundant chemically active constituent, and interactions between these two substances have produced a variety of other compounds (Table III, Figure 3).

Titan is small enough (slightly bigger than Mercury) so that products of atmospheric photochemistry can accumulate on the surface. Unfortunately, that surface is so cold (– 178 °C) that further chemical reactions seem unlikely, even though much of the surface may be covered by a liquid substance – oceans of ethane! Nevertheless, Titan offers us a laboratory in which the first steps in chemical evolution are still taking place today. All the resulting chemicals are preserved at low temperature for billions of years, just waiting for our investigations (Figure 4).

Obviously we may expect some planets to exhibit combinations of primary and secondary atmospheres. In fact, the most recent studies of abundances in outer planet atmospheres suggest that all of these giants have such compound atmospheres: C/H is greater than the solar value. Evidently the accumulation of an ice-rock core accompanied by degassing is followed by capture of an atmosphere from the primordial

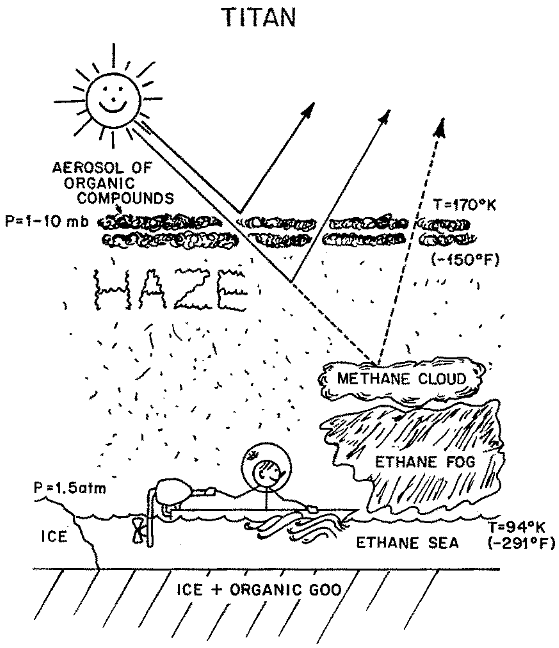

Fig. 4. A schematic cross-section of Titan's atmosphere showing the depths from which radiation of various wavelengths emerges. Liquid ethane may cover the surface or may collect in pools.

nebula. Titan itself is apparently still acquiring oxygen in the form of infalling icy debris.

The solar wind alone can contribute an extremely tenuous atmosphere to an otherwise airless body. This is the case for the planet Mercury, but this special type of atmosphere is much too thin to be of interest for our purposes. Nor is the otherwise fascinating, locally transient atmosphere of SO_2 associated with the active volcanoes of Io. We are seeking atmospheres thick enough to sustain conditions appropriate to carbon-and-water-based life.

4. The Inner Planets: Why Is Earth Unique?

This quest takes us back to our immediate neighbors in the solar system, Venus and Mars. As we have seen their early histories should have been very similar to Earth's. Why is it, then, that they have turned out so differently from us? Both of these planets have atmospheres dominated by carbon dioxide and no liquid water on their surfaces (Table IV). On Venus, the atmosphere is so dense that it has become an extremely efficient absorber of infrared radiation emitted by the planet's surface, thereby producing a huge greenhouse effect that keeps that surface hot enough to melt lead (475 °C). On Mars, in contrast, the atmosphere is so thin it does almost nothing to warm up the planet. The pressure it exerts on the Martian surface is so low that water cannot exist as a liquid – it would boil at its freezing point!

TABLE IV(a)

The composition of the Martian atmosphere

(A) Lower atmosphere

Gas	Abundance
CO_2	95.32%
N_2	2.7
Ar	1.6
O_2	0.13
CO	0.07
H_2O	0.03*
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	0.04–0.2 ppm*

(B) Upper atmosphere (above 100 km)

Gas	Concentration
NO	$10^{-4} \times CO_2$
O	$0.5–1.0 \times 10^{-2} \times CO_2$
H	$3 \times 10^4\,cm^{-3}$ above 250 km

* Variable with season and location (see text).

TABLE IV(b)

The composition of the atmosphere of Venus*

CO_2	96.5%
N_2	3.5%
^{40}Ar	33^{+33}_{-11} ppm
^{36}Ar	30^{+20}_{-10} ppm
O_2	30^{+38}_{-22} ppm
CO	20 ± 0.4 ppm
^{20}Ne	9^{+20}_{-6} ppm
SO_2	150^{+78}_{-55} ppm (at 22 km)
H_2O	<0.5% (conflicting measurements)
Kr	<69 ppb
Xe	<120 ppb

* Considerable disagreement still exists among various measurements [Hoffman *et al.*, *J. Geophys. Res.* **85**, 7871–7881 (1980); Donahue *et al.*, *Geophys Res. Lett.* **8**, 513–516 (1981)].

We can begin to see the problem. We seem to have a case of Goldilocks and the three planets: Venus is too hot, Mars is too cold, and the Earth is just right. We can test this idea with some hypothetical experiments. Suppose we moved Earth closer to the Sun, putting it at the distance of Venus. The resulting increase in average global temperature would cause the oceans to warm up, producing more water vapor in the atmosphere which would trap more radiation from the planet's surface, thereby increasing the temperature further until finally the oceans boiled away and the atmosphere contained all the water. At this stage solar ultraviolet light would break down the water very efficiently, the hydrogen would escape, and the oxygen left behind would gradually combine with other gases and the rocks.

The trapping of infrared (heat) radiation from a planet's surface by its atmosphere is called the greenhouse effect. In a gardener's greenhouse, the panes of glass substitute for the planet's atmosphere, allowing visible light from the Sun to pass through to warm the soil and then blocking the infrared radiation emitted by the soil.** The situation we have just described in our hypothetical experiment – moving the Earth to the orbit of Venus – could then be described as a "runaway greenhouse", since a feedback loop is established between the heating of the surface and the blocking of the resulting thermal radiation.

This provides a natural explanation for the absence of water on Venus today – it simply boiled away and was destroyed by photolysis. Until 1983, there was an attractive alternative explanation: perhaps Venus formed with no water. But analysis of Pioneer Venus mass spectrometer data have shown that the value of D/H in the atmosphere of Venus is 1.5×10^{-2}. This very high value demonstrates that a huge quantity of hydrogen has escaped from Venus, equivalent to the amount in 0.3 % of the Earth's oceans. Furthermore, this is only a lower limit on the original reservoir of water required to produce the escaping hydrogen. No other source of hydrogen is plausible. Thus the lesson from Venus is that a planet much closer to the Sun than our present position cannot retain oceans of liquid water.

But what if we move the Earth farther away from the sun? In this case the situation is not so clear. We can anticipate that for the present Earth, the consequences would be the equivalent of a 'runaway refrigerator': the mean temperature would decrease, more snow and ice would accumulate at the poles, increasing the planet's reflectivity, thereby

TABLE V

The atmospheres of Venus, Earth and Mars: volatile inventories of main constituents

Gas	Venus (Now)	Earth (Total)*	Mars (Total)*
CO_2	96.5%	98%	98%
N_2	3.5%	1.9%	1.7%
^{40}Ar	33 ppm	190 ppm	300 pppm
H_2O	Trace	3 km†	30 m†
Total Atm $10^6 \times \frac{Matm}{Mplanet}$	100	60	2

* No Life, no weathering, (total amount of volatiles degassed by the planet over geologic time).

† Thickness of a condensed layer of liquid water spread over the planet.

** In the gardener's case, the dominant warming effect is actually caused by the inhibition of convection.

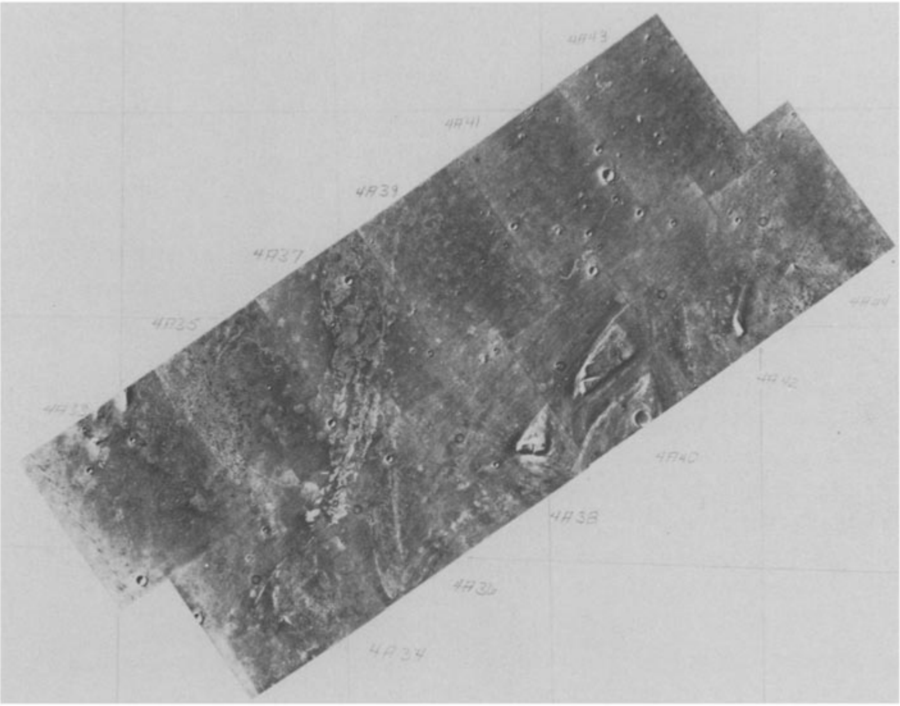

Fig. 5. A region of the surface of Mars showing evidence of erosion caused by running water. The wide variety of channels found on Mars suggest that there were both different episodes and different forms of water activity. A comprehensive history of these events is still lacking.

lowering the temperature further, etc. *But*, if we just changed the composition of the atmosphere, increasing the amount of carbon dioxide, we would be able to maintain clement temperatures by means of the resulting enhanced greenhouse effect. In fact we can calculate that the early atmosphere of Mars itself was probably much denser than the present one, with a surface pressure close to ours today and consisting primarily of carbon dioxide. Under these conditions, liquid water could exist on Mars, and we have a natural explanation for the widespread appearance of surface features apparently caused by running water (Figure 5, Table V). It is possible that life originated on Mars during this early epoch, only to die out as the climate deteriorated.

Why then, did Mars change to its present arid, nearly airless state? The problem seems to be linked to the planet's small size. Evidently Mars began with a poorer endowment of gases than the earth, and was also unable to degas them as completely, since it did not have as active an internal heat source. There is no evidence of plate-tectonics on Mars, and the huge size of the Martian volcanoes is itself a clue that the crust has remained stationary over the regions where magma was rising. We imagine then that the original carbon dioxide dissolved in those early waters and attacked the rocks as carbonic acid. The resulting carbonate rocks represented a net loss of carbon dioxide from the atmosphere, with a concurrent diminishing of both the surface pressure and the greenhouse effect. As this continues, one gradually ends up with the environment we find today.

But if Mars had been bigger, the situation could have been very different. Continual outgassing of carbon dioxide might have maintained much more clement conditions. We need not look for an exact duplicate of the Earth. Perhaps instead we would find a planet with a temperate equatorial zone, frozen at higher latitudes. The ice coating would reduce weathering, giving the carbon dioxide a longer atmospheric lifetime. But we might also need to invoke a form of life that flourishes with a much larger amount of this gas in the atmosphere than life on Earth seems to find ideal.

In any case, the *outer* bound to the zone around our Sun where we might expect to find habitable planets appears to be much less constrained than the inner bound. There is little we can do to cool off a planet if we move it closer to the Sun, but we can easily warm it up if we move it out, simply by changing the atmospheric composition. Indeed, there is a great worry among scientists today that the increase in the carbon dioxide content of the *Earth's* atmosphere resulting from the burning of fossil fuels is leading to a general warming of our planet that could have serious consequences on the global climate. If we could just slowly move the Earth away from the Sun as the carbon dioxide abundance increased, we would preserve the same global climate!

Working backwards in time, we can estimate what the present atmosphere on Earth would be like if there were no life and no liquid water. In the absence of these two weathering agents, Earth would not have formed all the carbonate rocks we find today. Replacing the equivalent of this carbon dioxide in the atmosphere, we would obtain a surface pressure roughly 60 times the present value, and an atmosphere that was 95% carbon dioxide. In other words, we would have effectively turned Earth into Venus (Table V). This gives us some sense that our ideas about the evolution of these inner planet atmospheres are generally correct. But the latest spacecraft data on the abundances of noble gases in the atmosphere of Venus show a distinctly different pattern from that found on Earth, indicating that we have more work to do before we can claim to have a complete theory.

5. Conclusions

We began this inquiry by asking why the Earth was apparently the only planet in the solar system with abundant life. We found that the key ingredients for life as we know it on Earth are liquid water and carbon. While there are undoubtedly clouds of liquid water in the atmospheres of some of the giant planets – especially Jupiter – these objects have no solid surfaces on which the water can collect. This seems important, since we need places where chemicals formed in the atmosphere can be concentrated and undergo further reactions. Theories for additional processing of these chemicals often invoke the catalytic action of surface minerals, especially clays. So we may need to add the presence of a solid surface to our minimal list of conditions necessary for the origin of life.

On the other hand, the atmospheres of the giant planets do contain the basic elements required for the production of organic molecules, and several kinds of non-equilibrium chemistry appear to be taking place. These reactions are important for what they can tell us about the similar spontaneous chemistry that took place on the primitive Earth. An especially interesting example is the satellite Titan, which does have a solid surface on which the reaction products from the atmospheric chemistry can accumulate. They will be preserved at low temperatures – probably in a bath of liquid ethane – for billions of years.

It is only in the inner solar system that we find planets with solid surfaces potentially warm enough to be covered with liquid water. Of the four inner planets, only Earth has both the right distance from the Sun and the right size for this fundamental condition to exist. We can imagine a situation in which a planet as big as the Earth could be a life-harboring world at a greater distance from the Sun – we need only add more carbon dioxide to its atmosphere. But we cannot move it much closer to its central star, since there is no way to keep it appropriately cool.

So we have the answer to our question: the Earth is the only planet in our solar system with abundant life today because it is at the right distance from the sun to allow water to be a liquid on its solid surface, and it is big enough to have acquired a large store of volatiles which it can vigorously degas and recycle by means of its tectonic activity. Yet the Earth is not so big that it would not permit hydrogen to escape because of its strong gravitational field.

How likely is it that there are other planets like ours, elsewhere in the galaxy? We must admit that at the present time we have no way of answering this question rigorously. Of the three largest inner planets in our solar system, two are the right size and one is in the right place. This might suggest to us that one in three solar systems should have an Earth-like planet, perhaps two in three if we accept the possibility that life on Earth might be possible at the distance of Mars, depending on atmospheric and biological evolution.

But until we discover and explore another solar system, we will have no idea how representative ours is. This discovery might come through the careful efforts being made by several different teams of astronomers to detect unseen planets by the effects of their motions on the stars they orbit. But clearly the most exciting (and informative!) discovery of other planets would arise from the detection of signals from civilizations that inhabited them. What the exploration of our own solar system has told us so far is simply that we see no barriers to the existence of such civilizations. If solar systems are common, Earth-like planets should not be rare. Given such a planet, the initial steps toward the origin of life seem remarkably easy. We can push these conclusions further by returning to Mars and Titan for additional studies at higher levels of sophistication than we have used thus far. Such missions are under consideration at the present time, but may not be implemented until late in the next decade.

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