# Giant Planets: Clues on Current and Past Organic Chemistry in the Outer Solar System

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The giant planets of the outer solar system—Jupiter, Saturn, Uranus, and Neptune—were formed in the same flattened disk of gas and dust, the solar nebula, as the terrestrial planets— Mercury, Venus, Earth, and Mars—were. Yet, the giant planets differ in some very fundamental ways from the terrestrial planets. As the name would indicate, the giant planets are both bigger and more massive than the terrestrial planets. The sizes of the giant planets range from about 4 to about 11 times that of the Earth and their masses from about 15 to 300 times that of the Earth. Hydrogen and helium are the most abundant elements in the atmospheres of the giant planets, just as in the Sun. However, nitrogen, oxygen, and carbon are the most abundant elements in the atmospheres of Venus, Earth, and Mars, the three terrestrial planets with significant atmospheres.
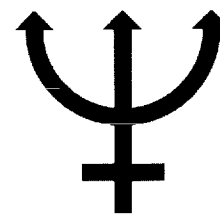
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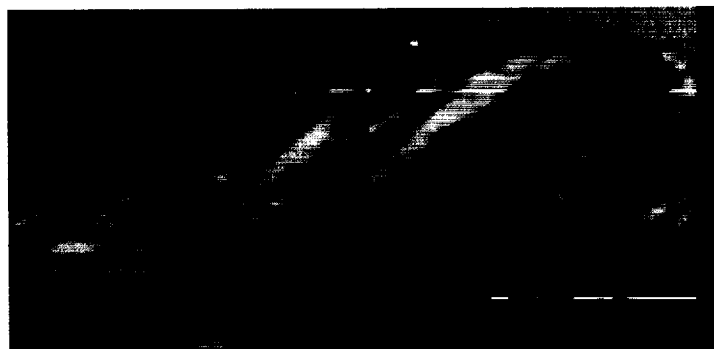
Furthermore, the atmospheres of the giant planets extend about ten thousand to several tens of thousands kilometers into the interiors of the giant planets, thereby representing a significant fraction of the entire mass of these planets, whereas the atmospheres of the terrestrial planets have much smaller depths and constitute only a tiny fraction of these planets' masses. Finally, numerous moons and rings surround each of the giant planets, whereas the terrestrial planets have no rings and at most two moons (Mars).

Despite these enormous differences, the giant planets are relevant to exobiology in general and the origin of life on the Earth in particular. The chemical steps that led to the first genetically reproducing organisms are widely believed to have involved the production of complex carbon-containing molecules from simpler carbon-containing molecules that occurred in a reducing environment (little free oxygen was present). The atmospheres of the giant planets represent highly reducing environments, in which one of the simplest carbon-containing molecules—methane—is being converted into more complicated molecules. Thus, these atmospheres represent natural laboratories for observing and

understanding some of the initial chemistry that leads to the production of organic molecules. Furthermore, the compositions of the atmospheres of the giant planets provide important constraints on the composition and abundance of carbon-containing molecules in the outer part of the solar nebula which, therefore, lead to insights on possible sources of carbon and other biologically relevant materials for the origin of life on Earth. Finally, if these materials came to Earth from the outer solar system, as they may have, the giant planets played a fundamental role in transferring this material to the inner solar system by virtue of their gravitational interactions with small bodies.

This chapter begins with the giant planets as they are today, and discusses their basic properties and the chemistry that is occurring in their atmospheres. Then, the chapter explores theories of their origin and stress aspects of these theories that may have relevance to exobiology and the origin of life on Earth.

Properties of the Giant Planets

The giant planets are made of three basic materials: gas, ice, and rock. Gas refers to compounds that are made almost exclusively of the elements hydrogen and helium; ice refers to those containing mixtures of water and carbon- and nitrogen-containing materials; and rock refers to ones made of mixtures of silicon, magnesium, iron, oxygen, and other heavy elements. This separation reflects the differing abilities of materials in these three classes to condense in different parts of the solar nebula. The gas component did not freeze out anywhere in this nebula; the ices, especially water, condensed in the outer part of the nebula, where the giant planets formed; and rock also condensed in the inner part of the solar nebula, where the terrestrial planets formed. Thus, the terrestrial planets are composed almost exclusively of rock, whereas the giant planets are made of varying proportions of all three materials. These names are merely meant to define compositional classes. The deep interiors of the giant planets are hot enough to melt and vaporize rock and ice-containing compounds that are located in them.
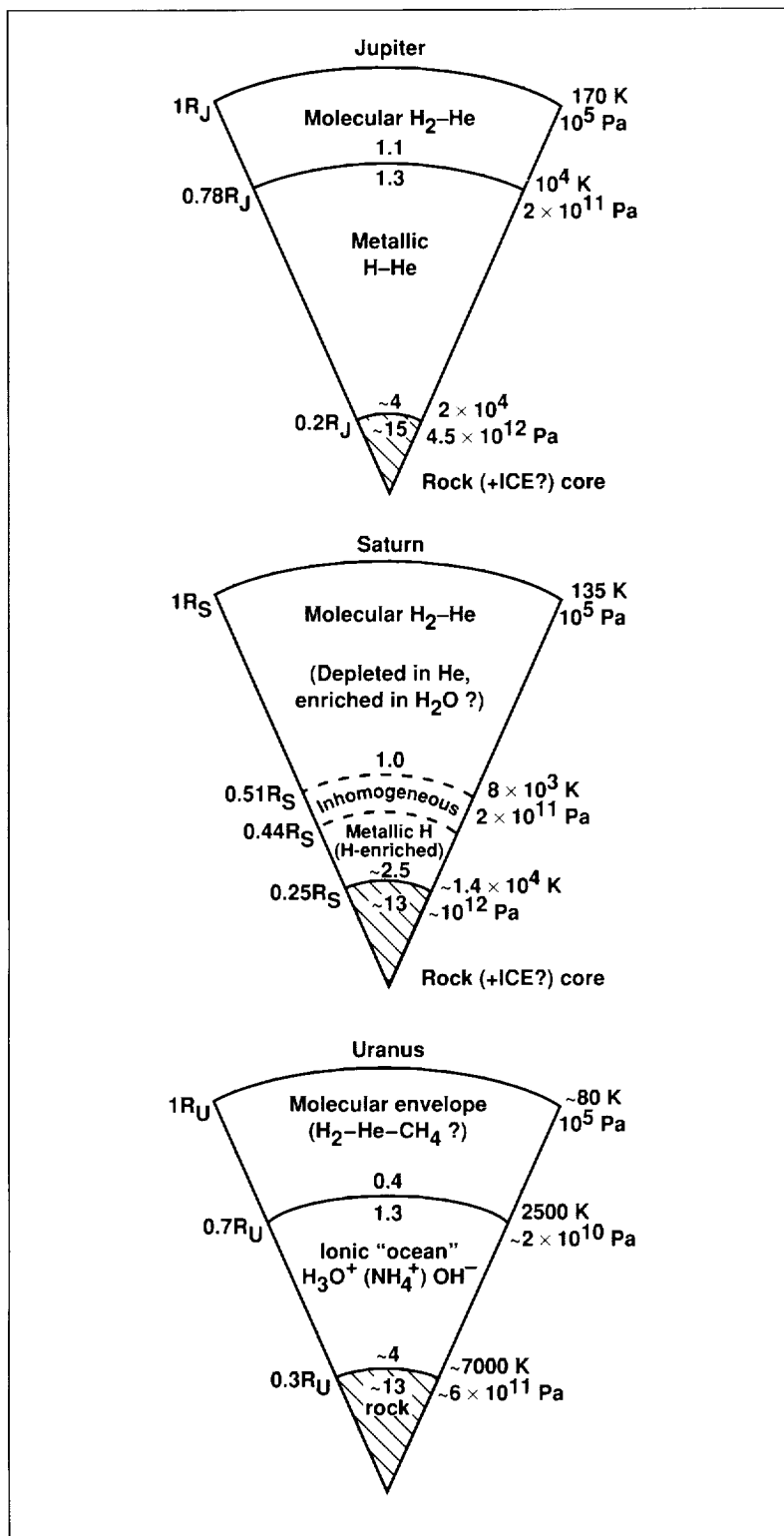
Jupiter

1R$_J$

Molecular H$_2$–He
1.1

170 K
10^5 Pa

0.78R$_J$

1.3

10^4 K
2 × 10^{11} Pa

Metallic
H–He

0.2R$_J$ ~4   ~15

2 × 10^4
4.5 × 10^{12} Pa

Rock (+ICE?) core

Saturn

1R$_S$

Molecular H$_2$–He

(Depleted in He,
enriched in H$_2$O ?)

135 K
10^5 Pa

1.0

0.51R$_S$ Inhomogeneous

0.44R$_S$ Metallic H
(H-enriched)
~2.5

8 × 10^3 K
2 × 10^{11} Pa

0.25R$_S$ ~13

~1.4 × 10^4 K
~10^{12} Pa

Rock (+ICE?) core

Uranus

1R$_U$

Molecular envelope
(H$_2$–He–CH$_4$?)

~80 K
10^5 Pa

0.4

1.3

0.7R$_U$

Ionic "ocean"
H$_3$O$^+$ (NH$_4^+$) OH$^-$

2500 K
~2 × 10^{10} Pa

~4

0.3R$_U$ ~13
rock

~7000 K
~6 × 10^{11} Pa

igure 5-1 illustrates the interior structures of the giant planets that have been derived by fitting physically based models to such properties as their masses, sizes, and mass distributions (or more precisely, their gravitational moments). The outer shells or envelopes of the giant planets are composed primarily of the gas component. Elemental hydrogen occurs as molecular hydrogen in the outer part of these envelopes. However, sufficient pressures are reached in the deeper parts of the envelopes of Jupiter and Saturn (pressures in excess of several million times that at the Earth's surface) for molecular hydrogen to be pressure dissociated and ionized into a highly electrically conducting form, metallic hydrogen. It is within these regions that the strong magnetic fields of Jupiter and Saturn are produced.

Figure 5-1. Schematic representation of the interior structure of the giant planets. Neptune has a structure similar to that of Uranus and so it is not shown. The numbers on the left show distance from the center in units of the planet's radius; the numbers on the right show pressure and temperature in units of pascals (=10^{-5} bars) and degrees Kelvin, respectively; and the numbers in the center show density in units of that of liquid water.

Table 5-1: Properties of the Giant Planets

Property	Planet			
	Jupiter	Saturn	Uranus	Neptune
Distance from Sun (Earth's distance = 1)	5.20	9.55	19.22	30.11
Radius (Earth's radius = 1)	11.27	9.44	4.10	3.88
Mean density (water = 1)	1.31	0.69	1.19	1.66
Total mass (Earth's mass = 1)	318.1	95.1	14.6	17.2
Mass of gas component	254–292	72–79	1.3–3.6	0.7–3.2
Mass of rock and ice	26–64	16–23	11–13.3	14–16.5
Axial inclination (degrees from normal to orbital plane)	3.1	26.7	98.0	29
C/H (solar = 1)	2.3	5.1	35	40

Near the central regions or cores of the giant planets, ice and rock are the dominant materials. It used to be thought that ice and rock were totally or almost totally segregated from the gas parts of the giant planets. However, there is an increasing amount of evidence indicating that some mixing of these materials has occurred. Thus, the envelopes contain a significant fraction of the planets' bulk content of rock and ices and the cores, at least in the case of Uranus and Neptune, contain some gas.

The giant planets are not simply different sized versions of the same thing, but exhibit a wide variation in their basic properties, as summarized in table 5-1. Not only do their masses and sizes vary considerably, but so does the relative proportion of gas and ice plus rock. It is cur-rently not possible to unam-biguously separate the rock and ice components. Massive Jupiter is made mostly of gas, whereas less massive Uranus and Neptune are composed primarily of ice and rock. Saturn is made primarily of gas, but has a larger fractional abundance of ice and rock than does Jupiter. An impor-tant point for later consider-ation is that the masses of the rock plus ice components of the four giant planets are the same within a factor of several, whereas the masses of the gas component vary by a factor of 100.

The very outer portion of the envelopes of the giant plan-ets, their atmospheres, is the part that can be photo-graphed and directly sensed with a wide variety of instru-ments. As shown in the chapter frontispiece, there is a wide diversity in the appear-ances of these observable atmospheres, with Jupiter showing an incredible range of structures and colors and Uranus being almost feature-less. This diversity reflects a combination of the densities and locations of the cloud layers in these atmospheres, the strength of the atmo-spheric motions, and the nature of the coloring agents that are produced in these atmospheres.

It is convenient to divide these atmospheres into two major regions, by analogy to a similar division for the Earth's atmosphere. Within the deeper lying troposphere, temperatures increase con-tinually with increasing depth, whereas the reverse is true of the stratosphere. The temperature inversion of the Earth's stratosphere is due, in part, to the absorption of sunlight by ozone, whereas the inversion of the outer

planets' stratospheres is caused by sunlight being absorbed by gaseous methane and small particles or aerosols. In both cases, the stratosphere's ability to cool by emitting thermal radiation diminishes with increasing altitude (decreasing density) and this abets the production of the inversion. Below the uppermost parts of the troposphere, temperatures in all four atmospheres increase as rapidly as is physically possible, at the adiabatic lapse rate. This is the rate established when there is efficient convection. Heat released from the deep interiors of the giant planets helps to drive the convection. Indeed, about half the energy radiated by Jupiter, Saturn, and Neptune is derived from internal heat, with the rest coming from absorbed sunlight. Internal heat contributes a small fraction (as yet unmeasured at the time this paper was presented) to the thermal radiation emitted by Uranus. By contrast, all but a tiny fraction of the radiation the Earth emits to space is due to absorbed sunlight.

Extremely low temperatures occur at the tropopause, the boundary between the stratosphere and the troposphere. Values of approximately 50, 50, 80, and 100 K characterize the tropopauses of Neptune, Uranus, Saturn, and Jupiter, respectively. As a result of the progressively lower temperatures with increasing altitude in the upper tropospheres of the giant planets, a series of ice condensation cloud layers form. In the cases of Jupiter and Saturn, first water clouds, then ammonium hydrosulfide clouds (formed from hydrogen sulfide and ammonia gases), and finally ammonia clouds form as the tropopause is approached (fig. 5-2). In the cases of Uranus and Neptune, even methane condenses in the upper troposphere, where it forms the highest cloud layer. The next cloud down in these atmospheres may be made of hydrogen sulfide, rather than ammonia ice, due to differing proportions of hydrogen sulfide and ammonia in these planets' atmospheres as compared to those of Jupiter and Saturn.

Figure 5-2. Schematic structure of the atmospheres of the giant planets.
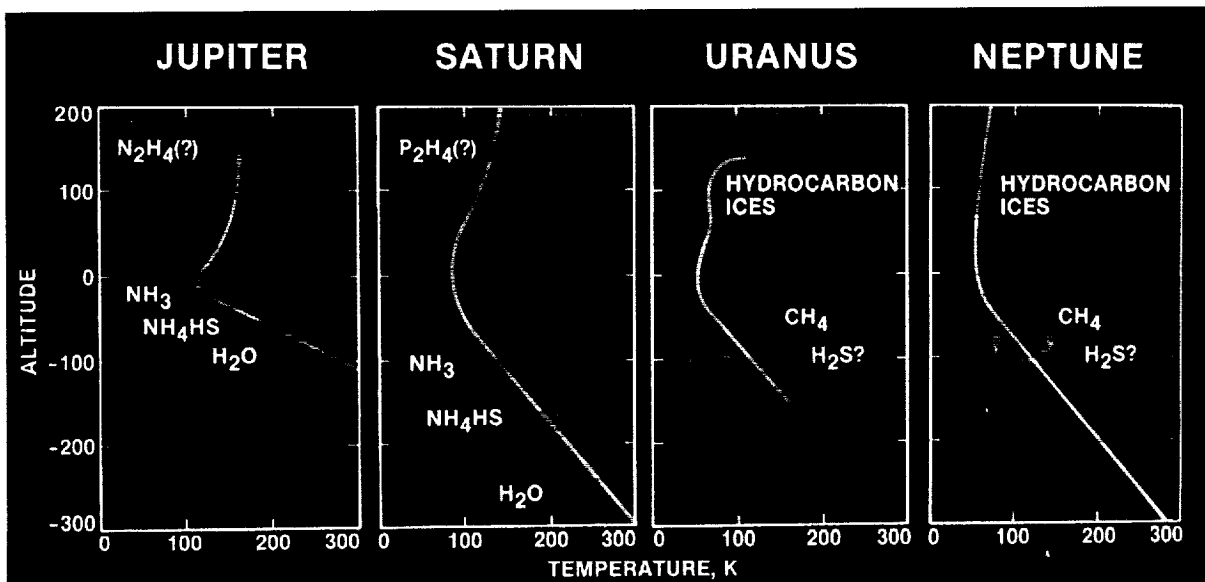
Chemistry

If an outer planet atmosphere was in local thermodynamic equilibrium, only the most stable molecules and atoms would be present. In this case, methane (CH_4) would be essentially the only carbon-bearing molecule and ammonia (NH_3) would be the only nitrogen-bearing molecule at the relatively low temperatures and moderate pressures that characterize these atmospheres. However, small amounts of molecules having more than one carbon atom, such as ethane (C_2H_6) and acetylene (C_2H_2), have been detected in the stratospheres of these planetary atmospheres, and small quantities of carbon monoxide (CO) and hydrogen cyanide (HCN) have been detected in Jupiter's troposphere. Even such exotic molecules as germane (GeH_4—four hydrogen atoms combined with a single atom of germanium) and phosphine (PH_3—three hydrogen atoms combined with a single atom of phosphorus) have been detected in the tropospheres of Jupiter and Saturn.

Marked departures from local thermodynamic equilibrium, as illustrated by the presence of the above species, arise from a combination of local energy sources producing them from the more stable compounds and from vertical motions carrying molecules from the deep interior, where a different thermodynamic state occurs, to the observable atmosphere. Key energy sources for driving atmospheric chemistry include solar UV radiation, lightning, and high energy charged particles (protons, heavy ions, and electrons) that are precipitated into the auroral zones from the Van Allen belts, or magnetospheres, surrounding these planets.

Despite the fact that the amount of solar energy reaching the giant planets is small—at Jupiter, only 4%, and at Neptune, a meager 0.1%, of that at the Earth—the chemistry of methane, and, for that matter, of virtually all constituents in their atmospheres, is controlled largely by the available solar flux. This is evident from the relative strengths of the various energy sources at Jupiter, listed in table 5-2. The UV portion of the solar energy at Jupiter amounts to just 1% of the total; it is, nevertheless, this radiation which is responsible for initiating the photochemical processes. The photons or quanta of light at UV wavelengths are sufficiently energetic to break the chemical bonds of stable molecules and therefore are the ones of interest for atmospheric chemistry.

Lightning can be potentially important in producing certain disequilibrium species such as HCN and CO. Energetically charged particles

Table 5-2: Energy Sources for Chemistry at Jupiter

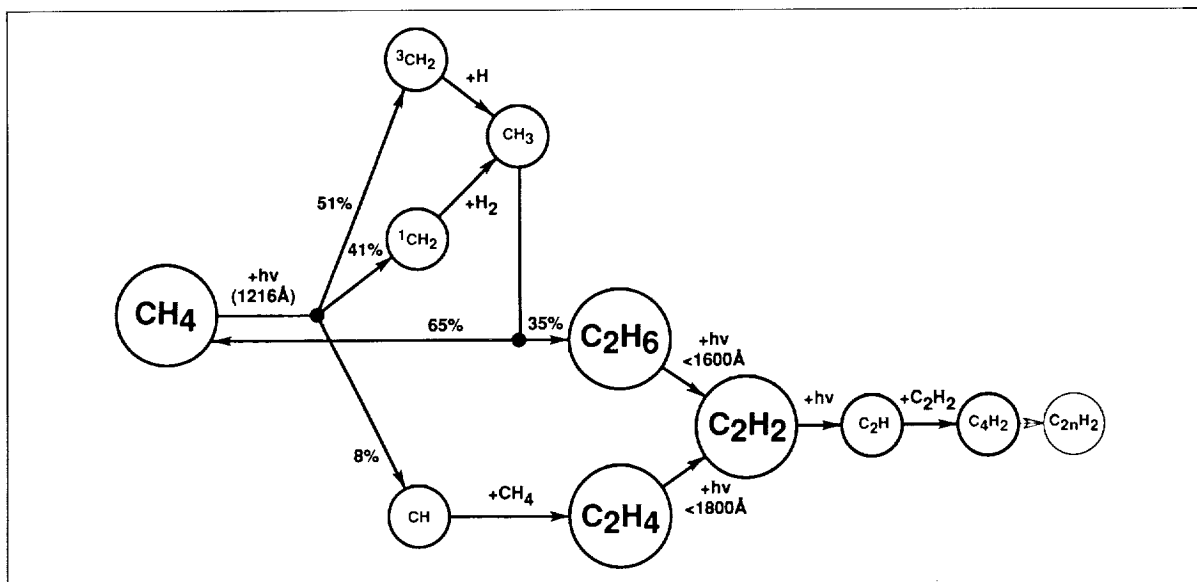|	
Solar energy	
Total incident, F_T	5×10^4 erg cm^{-2} s^{-1}
Ultraviolet, F_{UV}	~1% of F_T
Lightning (electric currents)	
+ Thunder (acoustic waves)	0.001% of F_T (terrestrial), could be as high as 0.003% of F_T at Jupiter
Magnetospheric (auroral)	
Total input	10^{13} W, or 10 erg cm^{-2} s^{-1} 0.02% of F_T
Globally averaged	0.4 erg cm^{-2} s^{-1}, or 0.001% of F_T

C-2

Figure 5-3. Schematic of the principal pathways for methane photochemistry in the atmospheres of the giant planets.

may play a role in the chemistry at high latitudes, where the auroral zones occur, perhaps resulting in the production of some heavier hydrocarbons and small particles (aerosols). The photochemistry of methane is discussed first in the following paragraphs, followed by a discussion of the effects of other energy sources.

The most significant pathways in the photochemical processes of CH_4 at Jupiter are shown schematically in figure 5-3. Although the photochemistry of methane is initiated by absorption of solar photons with wavelengths below 1450 Å, for all practical purposes it is the

extremely large solar flux at the Lyman-alpha wavelength of 1216 Å (a strong line of the abundant hydrogen atoms in the Sun) which is responsible for more than 90% of the bond-breaking or dissociation of CH_4 into molecular and atomic fragments. These fragments or radicals are very reactive and combine with themselves and other molecules to produce more stable compounds.

The photodissociation of CH_4 by the solar Lyman α line of hydrogen produces the CH_2 radical in its singlet (1) and triplet (3) states in roughly equal proportions. These states refer to the number of closely spaced energy levels characterizing the radical's lowest energy level. A small fraction (8%) of the CH radical is also produced. Note the conspicuous absence of CH_3, as it is kinetically forbidden as a CH_4 photodissociation product. Both states of CH_2 in turn produce the methyl radical, CH_3, on reaction with molecular hydrogen. The reaction of

CH_3 with itself produces C_2H_6; whereas the reaction of CH_3 with atomic hydrogen, H, recycles or regenerates methane. Nearly two-thirds of methane is recycled in this manner, thereby leading to no net production of more complicated molecules. The reaction of CH with CH_4 produces ethylene, C_2H_4. C_2H_4 and C_2H_6 photodissociate below 1800 Å and 1600 Å, respectively, to produce C_2H_2.

Ethane is highly stable in the atmosphere as it is largely shielded from the dissociative UV flux by the much more abundant methane, which also absorbs photons in the same wavelength range as ethane. Moreover, the photolysis rate of C_2H_6 is only 10% that of C_2H_4. Likewise C_2H_2 is also stable due to the low quantum efficiency (molecules produced per quantum of light absorbed) for its photolysis products, as well as rapid recycling of these products back to C_2H_2. The photodissociation of C_2H_2 proceeds slowly, resulting eventually in the formation of diacetylene (C_4H_2) and higher order polyacetylenes. In addition to the

above mentioned hydrocarbon species, methane photochemistry is expected to produce other higher order hydrocarbons, such as propane (C_3H_8), methylacetylene (C_3H_4), butane (C_4H_{10}), and even benzene (C_6H_6), a molecule with a ring structure. Thus, UV sunlight acting on methane in the stratospheres of the giant planets produces small quantities of ethane and acetylene, along with smaller amounts of more complex carbon compounds.

The fate of methane in the photochemical processes on the major planets is its conversion to heavier hydrocarbons with multiple carbon atoms. Eventually these heavier hydrocarbons would be removed from the stratosphere by condensation followed by rain-out or snow-out. In the deeper and warmer parts of the troposphere, the evaporation and thermal decomposition of these hydrocarbons, followed by high temperature-high pressure chemistry in the presence of molecular hydrogen, would regenerate methane. The latter would be convected up to the higher atmosphere, thus stabilizing this constituent on the major planets. In the absence of these and the stratospheric recycling mechanisms, all of the methane on Jupiter

would have been irreversibly destroyed in a few thousand years. Its present day abundance on the major planets attests to the effectiveness of these recycling processes.

Disequilibrium species, such as HCN, CO, PH_3, and GeH_4, have been detected in the visible atmosphere of Jupiter. Some have been seen on Saturn as well. None can be produced by conventional photochemical processes. The following paragraphs discuss some hypotheses for explaining their presence, and their significance.

HCN is an important precursor molecule for the formation of amino acids and proteins, which are important molecules in living organisms. The detection of HCN in the atmosphere of Jupiter poses a dilemma, as photochemical reactions fail to produce its observed abundance (2 parts per billion). Nevertheless, it is instructive to review these processes since the lack of complete information on some key reaction rates still makes them potentially important.

The photolysis of methyl-amine (CH_3NH_2) or ethyleneimine (C_2H_5N) is expected to produce HCN. These precursor molecules are produced by the coupling of the NH_3^- and CH_4^- photo-chemistries in a relatively narrow altitude range of the upper troposphere. The quantum yield of HCN from the photolysis of CH_3NH_2 is low. It is therefore not an important source of the observed quantity of HCN in the Jovian atmosphere. In the second case (C_2H_5N source), the rate of the reaction between NH_2 and C_2H_3 (which are intermediate products of the NH_3 and CH_4 photochemistries) that helps to produce it is not known; neither are the reaction kinetics of all the possible products. Thus, the photo-chemical source of HCN is, at best, speculative and only potentially important.

Another mechanism proposed for the formation of HCN is lightning. This source is also highly controversial. Light-ning discharges have been detected on long exposure images of the Jovian atmo-sphere obtained by the Voyager spacecraft. Lightning discharges produce HCN in a methane/ammonia atmo-sphere by temporarily raising the local atmosphere to very high temperatures, where reactions can proceed rapidly,

and by producing UV radia-tion. The possible importance of lightning for generating HCN and other disequi-librium species in Jupiter's atmosphere depends strongly on what assumptions are made about the fraction of the available energy in the atmosphere (that due to sunlight and heat convected from the interior) that is converted into lightning and the location of the lightning. For example, its occurrence near or within tropospheric water clouds could abet the production of some disequi-librium species, including CO as well as HCN.

Disequilibrium species such as PH_3, GeH_4, and CO are the major thermodynamical equilibrium forms of P, Ge, and C, respectively, in the unobservable, very deep, high temperature and pressure regions of the giant planets' tropospheres. Yet they have been detected in the observ-able atmosphere of Jupiter (PH_3 and CO have been detected in Saturn's strato-sphere also). Their presence in these atmospheres implies that either strong vertical mixing is transporting these compounds from great depths into the upper troposphere and/or stratosphere or that an extraplanetary source is

introducing significant quantities of the needed atoms (e.g., O for CO) into the atmosphere. The latter mechanism might be an important source for CO. Influx of oxygen-bearing species, such as water from infalling meteorites, comets, ring particles, and material derived from the planets' moons, could initiate a series of reactions with atmospheric hydrocarbons, which would eventually produce CO. However, recent measure-ments indicate that the fractional abundance of CO is higher in the troposphere than the stratosphere and, therefore, favor an internal source.

If the disequilibrium gases, GeH_4, PH_3, and CO, are derived from the deep tropo-spheres of Jupiter and Saturn, they need to undergo strong vertical mixing to bring them to the observable atmospheres before they can be entirely converted to their low-temperature, thermodynamic equilibrium forms. Since the rates at which this conversion occurs decrease very rapidly with decreasing temperature (and hence increasing alti-tude), the abundance of these disequilibrium gases in the atmosphere is essentially set by their abundances at a "quench" temperature, where the transport and reaction

rates are comparable. The quench temperature is the lowest value at which thermo-dynamic equilibrium is readily achieved.

The above mentioned mixing hypothesis is attractive from another viewpoint—that for explaining the color of the Great Red Spot (GRS) on Jupiter and other cloud features. (Other possibilities are noted in the next para-graph.) If PH_3 is indeed mixed up to the upper troposphere by strong upward transport, it is likely to undergo UV photolysis which could eventually yield triclinic red phosphorus crystals, $P_4(s)$, in the Jovian atmosphere. This chromophore resembles the color in the GRS and many other clouds on Jupiter and Saturn. Since the GRS may be a region of enhanced vertical motion, a larger amount of PH_3 might persist to near the top of the GRS clouds before undergoing chemical conver-sion to $P_4(s)$, thereby produc-ing a particularly strong coloration of the GRS.

Other possible candidates suggested for explaining these cloud colors include H_2S and some polyacetylenes. Gener-ally polyacetylenes are white; however, some as yet poorly understood chemistry could produce the appropriate color from these hydrocarbons. For example, solar UV radiation acting on solid polyacetylenes may produce more compli-cated forms that do absorb at visible wavelengths.

The photolysis of H_2S occurs below 3000 Å, and eventually produces elemental sulfur, S_8, which can be yellow, or hydrogen polysulfide, H_xS_y (x and y are various integers), which is orange, or ammo-nium polysulfide [$(NH_4)_xS_y$], which is brown. Thus a wide ranging choice of colors is possible as a result of H_2S photochemistry. This is attractive, as the colors of the Jovian clouds also range from yellowish red to orange to brown to red. The principal difficulty with the scenario is that the fate of H_2S on Jupiter and Saturn is most likely its removal by ammonium hydrosulfide (NH$_4$SH) cloud condensation before it could get a chance to be photolyzed (NH$_4$SH is formed by the reaction of NH_3 with H_2S). H_2S has not been detected in the upper troposphere of Jupiter (or any other giant planet). The upper limit on its fractional abundance at the 700 millibar level is

0.001 times the amount expected from the solar abundances of S and H. These observations seem consistent with its loss in the NH$_4$SH cloud just discussed. Further-more, because of a severe depletion due to scattering by Jovian air molecules, the 3000 Å and shorter wave-length photons that are needed for H_2S photolysis cannot penetrate to the level below these clouds (pressures greater than 2 bars) where it is available.

Another possibility is that, like CO, sulfur in some form might be brought into the upper atmosphere from an extraplanetary source. For Jupiter, such a source would presumably be the circum-Jovian Io plasma torus which is populated by sulfur ions derived from the explosive volcanoes of the moon Io. The incoming sulfur would react with the constituents in the Jovian upper atmosphere, producing perhaps CS, and even COS if oxygen is also being injected at the same time as sulfur. None of these major sulfur compounds have the color that matches the color in the clouds of Jupiter. A possibility exists that subsequent chemistry induced by energetic charged particles could produce trace species with the right color.

Sufficiently energetic charged particles, namely cosmic rays, penetrate to the deep troposphere where they could interact with H_2S or NH_4SH to produce species (such as S_8, H_xS_y, etc.) which have the colors of the clouds of Jupiter and Saturn. This would circumvent the difficulty associated with photolyzing H_2S. It would also apply equally to Jupiter and Saturn. Much laboratory work needs to be done before one can fully understand the implications of the charged-particle-induced chemistry on the giant planets. In any event, the striking and varying coloration of the clouds of Jupiter and Saturn strongly suggest the occurrence of chemical processes that produce complex molecules.

Origin of the Giant Planets

The composition of the giant planets provides useful clues and constraints on the manner in which they formed. First, they all contain large amounts of the gas component. This means that growth to their current masses was completed or almost completed before the gases of the solar nebula were dissipated. Based on the properties of young stars of comparable masses to that of the Sun, the T Tauri stars, the time scale for the formation of the giant planets was ten million years or less. Also, an efficient means of concentrating the nebula gases around the giant planets is required.

All the giant planets have a much larger fraction of the elements found in the ice and rock components, relative to hydrogen, than does the Sun. The degree of this heavy element excess varies from about a factor of 5 for Jupiter to 1000 for Uranus and Neptune. Thus, the giant planets accreted the solid phase of the solar nebula much more efficiently than its gas phase. This property suggests that the giant planets grew initially in the same way that the terrestrial planets did, but that they followed their own unique path of formation at a later stage.

Another important constraint on the formation of the giant planets is the similarity of their rock and ice masses and the dissimilarity of their gas masses. This constraint may imply that there is a rather abrupt transition in the accretion of the giant planets in which they switch from a solid-dominated accretion to a gas-dominated accretion. Furthermore, this transition point may have occurred at similar rock and ice masses.

Finally, the amount of carbon in the form of methane in the atmospheres of the giant planets, relative to hydrogen, is more than is found in the Sun. In particular, the carbon-to-hydrogen ratios in the atmospheres of Jupiter, Saturn, Uranus, and Neptune are about 2, 5, 35, and 40 times larger than the corresponding solar ratio and presumably that of the solar nebula (counting both solids and gases). This enhancement of carbon implies that some carbon was contained in the solid phases of the outer solar nebula (remembering that the giant planets preferentially accreted the solids) and that some of the carbon in the solid phase was mixed into the envelope.

The above considerations have led to the following hypothesis for the origins of the giant planets. The initial accretion of each of the giant planets was essentially identical to that of the terrestrial planets. Through a large number of gentle collisions, small solid bodies grew to successively larger sizes. In a given collision between two bodies, some of the kinetic energy of their relative motion before impact is dissipated upon impact, i.e., it is converted into other forms of energy, such as heat, sound waves, and fracturing. When the remaining kinetic energy is less than the energy due to either their mutual gravitational attraction or surface sticking forces, a composite body results. In a given region of the solar system, the largest of these growing bodies eventually interacted with and usually accreted all the smaller bodies or planetesimals, whose orbits crossed its orbit. Thus, ultimately the biggest accreting bodies attained masses comparable to or greater than that of the present Earth.

O nce the masses of the forming giant planets became large enough, they were able to begin gravitationally concentrating large amounts of gas from the surrounding solar nebula about themselves. The gas within a forming planet's sphere of influence cooled by
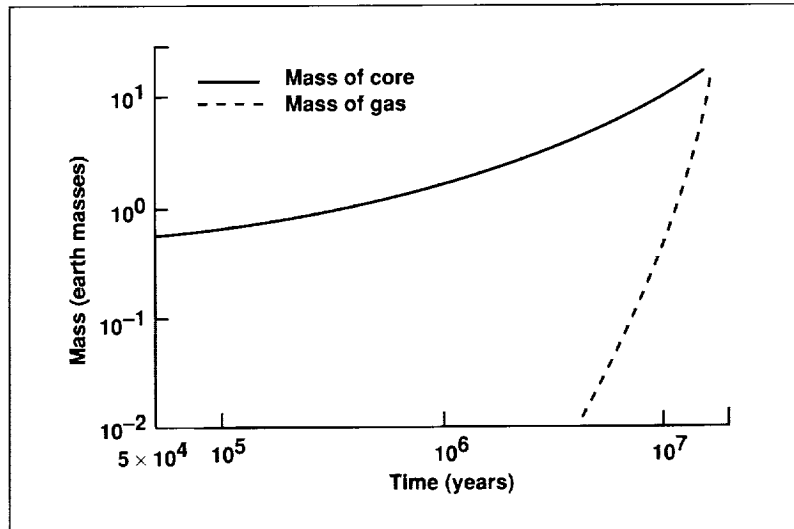

Figure 5-4. Envelope mass (dashed) and core mass (solid) as a function of time for a model of the growth of a giant planet for which the planetesimals were accreted at a constant rate of 10^{-6} Earth masses per year.

emitting thermal radiation to space and, as a result, the gaseous envelope contracted. This caused more gas to be added to the sphere of influence. Initially, the envelope's contraction rate was very slow and so the planet's mass was dominated by the solid planetesimals it had accreted. However, as the planet's mass approached ten to several tens of Earth masses, the rate of the envelope's contraction dramatically accelerated and soon a point was reached where accretion was dominated by the addition of gas from the surrounding solar nebula. This highly nonlinear relationship between the masses of the envelope and core is illustrated in figure 5-4. Once the envelope and core masses became comparable, subsequent growth was dominated by the gas component. This point of mass equality is sometimes referred to as the critical core mass, since a giant planet needed to attain this mass to add very large amounts of gas subsequently.

Simulations of the growth of the giant planets indicate that the value of the critical core mass is very insensitive to the pressure and temperature of the surrounding solar nebula, i.e., the distance from the Sun at which the planet formed. The critical core mass depends most sensitively on the rate of accretion of the solid planetesimals, with larger accretion rates implying a somewhat larger value. If we use the masses of the ice and rock component of the giant planets as a guide to the values of the critical core masses, we find that they should have formed in times comparable to or less than reasonable lifetimes for the solar nebula. From this perspective, neither the Earth nor the other terrestrial planets became giant planets because they did not achieve masses large enough to approach the critical value before the gas of the solar nebula was lost to either the Sun or interstellar space.

The similarity in the ice and rock masses of the giant planets may be attributed to the insensitivity of the critical core mass to their locations in the solar nebula and its weak dependence on the planetesimal accretion rate. However, a true gas runaway accretion phase appears to have been achieved only for Jupiter and Saturn, whose present gas masses exceed those of their ice and rock components. Conversely, Uranus and Neptune appear not to have quite reached critical core masses before the solar nebula was dissipated.

After Jupiter and Saturn achieved a critical core mass and runaway gas accretion commenced, they very rapidly added gas from the surrounding solar nebula. The amount of gas they ultimately accreted may have been limited by several processes. First, once the nearby gas was exhausted, the rate of gas accretion may have been limited by the time needed to transport gas from more distant places in the solar nebula to nearby places. Second, once the planet's mass became large enough, it may have exerted a strong enough gravitational tug on the surrounding nebula to push the nebula away from itself. This non-intuitive repulsive gravitational torque arises in multi-particle media, where frictional forces among the particles exist. This process is responsible for the ability of satellites to create gaps in the rings of Saturn.

At the time that the giant planets finished growing, they were much bigger than their current dimensions. The combination of their self-gravity and their cooling by radiation to space led them to commence a contraction phase that has continued to the present. At first this contraction was very rapid, but it became progressively slower as a larger fraction of the envelope attained high densities at which they started to behave more like an incompressible liquid than a compressible gas. During an intermediate stage in the contraction phase, a flattened disk of gas and dust, derived from either the solar nebula or their outer envelopes, developed around them. Satellites and rings formed in these circumplanetary nebulae. The above phases of growth and contraction in the history of the giant planets are summarized in figure 5-5.
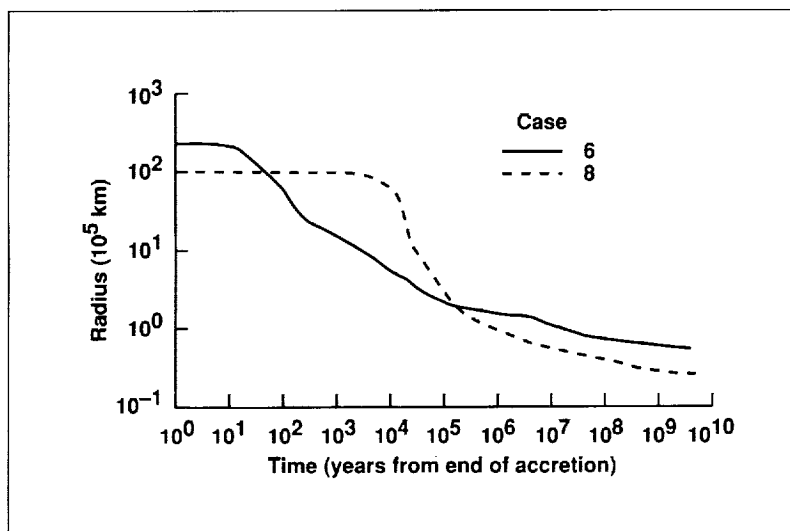
Figure 5-5. Radius of Saturn (solid) and Uranus (dashed) as a function of time from the completion of their accretion.

Composition of the Solar Nebula

The abundance of elements in all parts of the solar nebula is thought to have been identical to that in the early Sun and therefore close to that in the present Sun (only nuclear burning has altered the abundance of a few elements in the Sun). However, the abundances of elements incorporated into the planets that formed within the solar nebula depended on the partitioning of these elements among different chemical species in the solar nebula, the phase of these compounds (gas versus solid), and the mode of the planets' formation.

Of particular interest from an exobiological perspective is the partitioning of carbon, oxygen, and nitrogen atoms among various species and phases in the solar nebula. In strict thermodynamic equilibrium, carbon would have been sequestered almost entirely into carbon monoxide in the warmer regions of the inner solar nebula and into methane in the outer part of the nebula. Temperatures within the regions of the solar nebula where planets formed were probably too elevated for either of these gases to have condensed.

However, there are reasons for suspecting that significant departures from thermodynamic equilibrium may have occurred, especially in the colder parts of the nebula. First, chemical reactions may have occurred too slowly in the outer part of the solar nebula, even over its lifetime of several million years, to convert carbon from one chemical form (specifically CO) into its thermodynamic equilibrium form, methane. In particular, carbon monoxide flowing into the outer part of the solar nebula from either the inner part or from the molecular cloud from which the solar nebula formed may simply have remained in the form of carbon monoxide.

Second, complex organic molecules have been found in significant abundances in both certain types of meteorites, the carbonaceous chondrites, that are derived from the outer part of the asteroid belt, and in comets, such as comet Halley. This finding suggests that some carbon in the solar nebula was present as solid organic matter. It was not made biologically, but rather through a series of chemical transformations that occurred in interstellar space (and hence was present in the molecular cloud that gave

birth to the solar nebula) and/ or the solar nebula. Examples of such processes include ion-molecule reactions that produce observed complicated carbon molecules in interstellar space and the Fischer-Tropsch reaction, whereby carbon monoxide and hydrogen produce organic molecules in the presence of a solid catalyst.

In a similar vein, elemental nitrogen would be expected to have been in the form of molecular nitrogen in the inner solar nebula and ammonia in the outer solar nebula, if thermodynamic equilibrium was the controlling factor. However, slow reaction kinetics might have prevented ammonia from being the dominant nitrogen-containing species in the outer solar nebula. Also, some nitrogen may have been incorporated into organic molecules. However, it seems that nitrogen was less efficiently emplaced into organic compounds in the early solar system, based on the elemental composition of organics found in carbonaceous chondrites and comets.

Almost all the oxygen in the solar system was divided between water, carbon monoxide, and rock. Since the solar elemental abundance of carbon is about half that of oxygen, the abundance of water in the solar nebula depended strongly on the partitioning of carbon into its various possible forms. If no carbon was in the form of carbon monoxide, the water-to-rock ratio in the solar nebula would have been about 1.5, whereas if carbon was entirely in the form of carbon monoxide this ratio would have been about 0.4. In the inner solar system, almost all of the water would have been in the vapor phase, although some hydrated solid silicates could have been produced in the lower temperature portions of this region. In the outer parts of the solar nebula, where temperatures were less than half the room temperature value, water would have been almost entirely in its solid condensed state. Thus, the planetesimals forming the terrestrial planets contained little, if any, water, whereas those that formed the giant planets were rich in water.

Constraints on the partitioning of carbon among various species in the solar nebula can be derived from the composition of current solar system objects. We have already mentioned that the carbon-to-hydrogen ratio in the atmospheres of the giant planets exceeds the solar ratio by factors of few to several tens and that this enrichment of carbon is due to the partial mixing of planetesimal carbon into the envelopes of these planets. By modeling the observed carbon to hydrogen ratio, it is possible to estimate the fraction of the carbon in the outer solar nebula that was contained in the solid phase, perhaps mostly in the form of organics.

During the early growth of the giant planets, when their core masses were less than a few Earth masses, their envelopes were not very massive and all but the tiniest planetesimals would have been able to penetrate through the envelope and reach their cores relatively intact. However, during the later growth stages, when their core masses began approaching their critical values, all but the very largest planetesimals would have been vaporized in their now massive, hot envelopes. Over the entire course of their formation, perhaps 50 to 75% of all planetesimals would
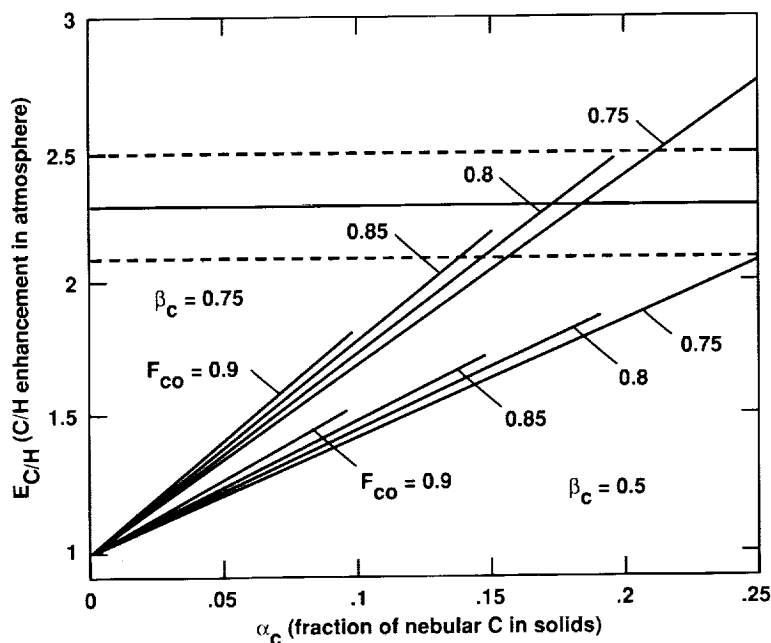
Figure 5-6. Predicted C/H ratio in the atmosphere of Jupiter (in units of the solar ratio) as a function of the fraction of the carbon of the outer solar nebula that was contained in solid bodies. The solid horizontal line shows the observed ratio and the dashed lines alternative values allowed by measurement uncertainties. The various slanting lines show predicted values for various choices of the fraction of nebular carbon in the form of CO, F_{CO}, and the fraction of planetesimals that dissolved in Jupiter's envelope during its formation, β_c.

have vaporized in their envelopes, thus providing carbon for their present atmospheres.

The fraction of nebular carbon, α_c, that was contained in giant planet-forming planetesimals can be found from the observed atmospheric abundance of carbon, the fraction of mass contained in the rock and ice components for the entire planet, and a reasonable value for the fraction of planetesimals that were dissolved in the planet's envelope during its formation, β_c. Figure 5-6 illustrates the value of α_c derived from data on Jupiter when β_c is set equal to 0.5. In this case, α_c equals about 0.2. Comparable values hold for the zones where the other giant planets formed, based once again on their observed atmospheric carbon abundances.

Estimates of the oxidation state of the gaseous carbon species in the outer solar nebula, i.e., the relative abundances of carbon monoxide and methane, may be obtained from the mean density of the solid planet Pluto. By virtue of a relatively unique orbit, Pluto crosses the orbital distance of Neptune, but never comes close to it. Thus, it may be one of the largest surviving planetesimals from the epoch of the formation of the giant planets. Pluto is also unique in having a close moon, Charon. In the last several years, Pluto and Charon have passed in front of one another, as viewed from the Earth. By measuring the characteristics of these mutual occultation events, astronomers have been able to derive a mean density for the Pluto/ Charon system, which is approximately the same as that of the more massive Pluto. Pluto's mean density is about 2 grams per cubic centimeter or about twice that of liquid water (at 4°C).

The mean density of a solid body in the outer solar system is determined primarily by the relative proportion of water and rock that it contains. If it was composed solely of water, its mean density would be about 1 gram per cubic centimeter, whereas if it were made entirely of rock, this value would be about 3.7 grams per cubic centimeter. Pluto's observed density implies that its bulk water and rock fractions are about 0.3 and 0.7, respectively.

As mentioned earlier, oxygen was partitioned in the solar nebula chiefly between water, carbon monoxide, and rock, with the implied relative abundance of water and rock varying significantly as the carbon monoxide abundance varied within limits allowed by solar elemental abundances. The water and rock fractions of Pluto inferred from its mean density indicate that much of the carbon in the region where it formed was in the form of carbon monoxide, as illustrated in figure 5-7.
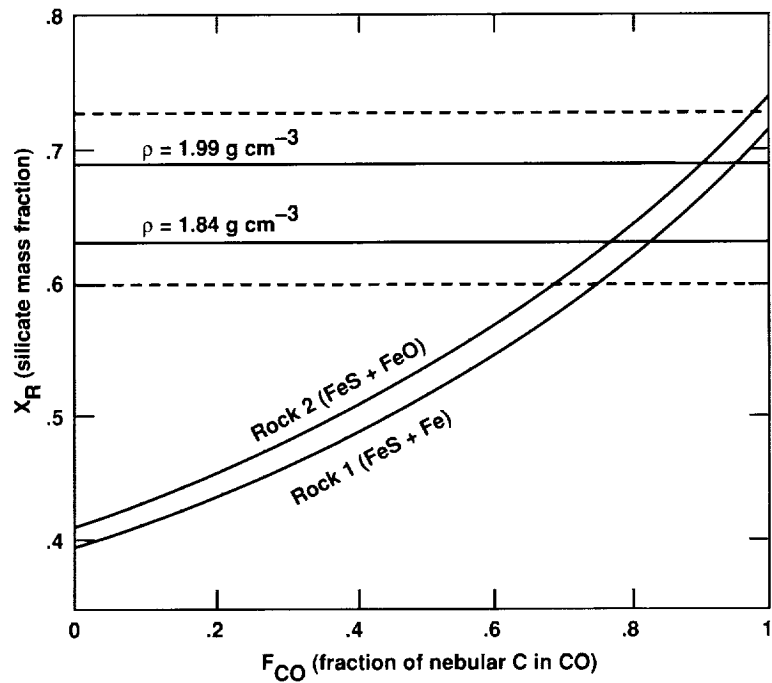

Figure 5-7. The fractional abundance of the rock component of Pluto (the rest is water) as a function of the fraction of carbon that was in the form of gaseous CO in the outer solar nebula. Two possible values of the rock fraction, as derived from Pluto's measured mean density, ρ, are shown by the solid horizontal lines, with their associated uncertainties (dashed horizontal lines). The two slanted lines show the predicted rock fraction for two choices of the composition of the rock.

The above discussion indicates that gaseous carbon monoxide was the chief carbon-containing species throughout the solar nebula. In the region where the giant planets formed a smaller fraction of carbon was present in the solid phase, perhaps chiefly as organics. By implication, gaseous molecular nitrogen was the chief nitrogen-containing species throughout the solar nebula, with a small fraction of the nitrogen (but less than the carbon fraction) in the solid phase.

Implications for Earth

Compared to solar elemental abundances, the Earth as a whole is highly deficient in the materials that are essential to life: water, carbon-containing, and nitrogen-containing species. The ratio of these compounds to rock for the Earth as a whole is about 0.00001 to 0.0001 by mass, as compared to values of about 0.1 to 1 from solar abundances. Yet, there is enough of these materials, particularly since they are concentrated near the Earth's surface, to have permitted life to have arisen some 4 to 4.5 billion years ago and to have sustained it until the present. By comparison, the giant planets and Pluto are rich in these volatile compounds, having abundances relative to rock that are comparable to that expected from solar abundances. Yet, no life has been detected on them to date.

The above stark difference in volatile abundances between the inner and outer solar system raises the question as to the ultimate source region for the volatiles that the Earth presently possesses. On the one hand, only very modest amounts of volatiles in the planetesimals that formed near the Earth and contributed the bulk of its mass would have sufficed to account for their present abundances. On the other hand, relatively small contributions to the Earth's mass from volatile-rich bodies formed farther out in the solar nebula could have provided the bulk of the planet's volatiles. For the moment, let us suppose that the latter is true and consider the role that the giant planets played in transferring volatile-rich planetesimals from the outer to the inner parts of the solar system.

When small bodies pass close to, but do not collide with, a planet, they have their direction of travel altered by the gravitational field of the planet. For a planet to be able to transfer the orbit of a planetesimal from its region of the solar system to that of other planets, the escape velocity from its surface (a measure of the strength of its gravitational field) needs to be comparable to or greater than the orbital velocity of the planetesimal. The giant planets met this criterion once they attained their current masses and once they contracted to a size comparable to their current size.

More precisely, Uranus and Neptune were then able to scatter planetesimals from their neighborhood either into the more distant regions of the solar system, where they may have formed the Oort cloud from which comets are derived, or to the orbit of Saturn. Saturn and, particularly, Jupiter were able to scatter the once scattered planetesimals originating near Uranus and Neptune, as well as their own planetesimals, into the inner part of the solar system. These scattered planetesimals, as well as ones removed from the asteroid belt directly or indirectly by Jupiter, were the principal contributors to a period of heavy bombardment that the terrestrial planets experienced during their first 700 million years of existence. During this epoch the terrestrial planets and the Moon were cratered by impacting bodies at a rate that was at least a thousand times greater than the current rate.
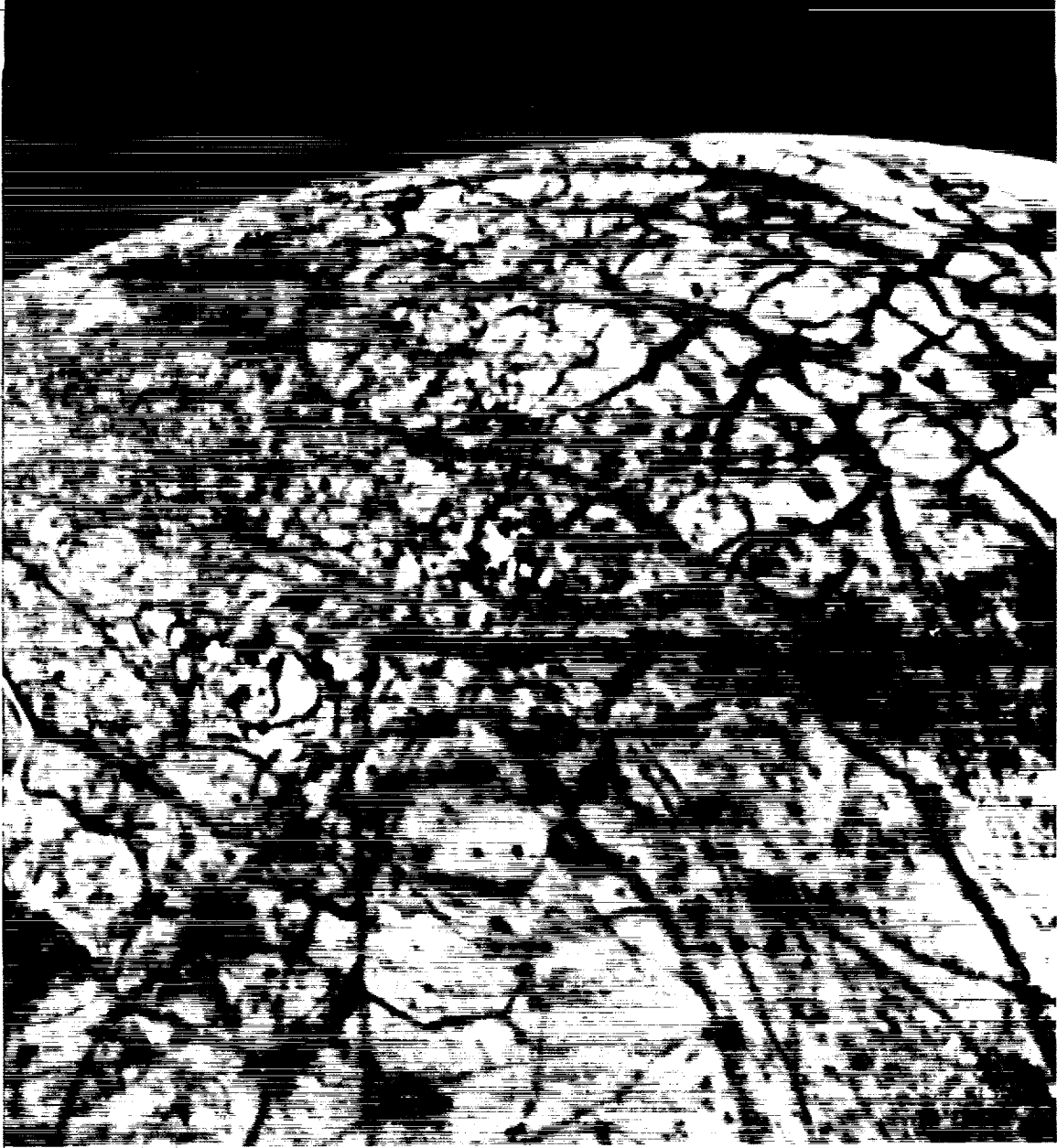
Thus, over a period that extended from the end of the Earth's formation through its early history, the Earth encountered a large number of bodies, some of which may have been very volatile-rich and therefore may have contributed significantly to its present volatile inventory. These bodies originated in or near the region of the outer planets and were scattered by them into the inner solar system. In this plausible, but not yet proven scenario, living organisms on Earth today, including ourselves, may be made in part of atoms that were situated at one time close to the region of the outer planets and that were brought to the Earth through the gravitational effects of these planets.

Additional Reading

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