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The Outer Solar System

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We now stand on the threshold of the exploration of the outer solar system. The first space probe which will fly by Jupiter, Pioneer 10, is on its way. A twin spacecraft, Pioneer G, will soon be launched. Later in the decade two Mariner spacecraft will be sent to fly by the planets Jupiter and Saturn, carrying out a comparative study of these two planets. The scientific results potentially available from these missions are of great importance.

It has been recommended that these flyby spacecraft be followed by planetary entry probes and orbiters to be launched in the early 1980's. The probe and orbiter missions might include Uranus as well as Jupiter and Saturn among the planets to be studied, and would be complementary to the flyby missions in very important ways. The flyby spacecraft will give us measurements of particles and fields in interplanetary space and in two planetary environments, and will result in measurements of numerous atmospheric properties. The orbiters will return these types of information in much greater detail for a single planet, and will also give information about selected satellites and about the interior of the planet. The entry probes will give detailed information concerning the structure and composition of a planetary atmosphere, including information from a considerable distance below the planetary cloud tops.

With these opportunities opening up, intensive studies have been made of the status of our scientific knowledge of the outer solar system, and of the technology required, in instrumenting spacecraft for missions to outer planets, to return worthwhile information about a wide variety of physical properties. The general scientific strategy for exploration of the outer solar system has been studied by a science advisory group organized by the Jet Propulsion Laboratory, Pasadena, California (*1*). Detailed problems of instrumentation and their relationship to expected scientific return have been considered by a science steering group (also organized by JPL), which consisted of 13 teams dealing with different types of instrumentation. As a result of these activities a rather hard look has been taken at our knowledge, or lack thereof, of the properties of the outer solar system.

In this article an attempt is made to give a more concise summary of the status of scientific thinking concerning the outer solar system, as reflected in the reports of these groups and in the current scientific literature. The outer solar system is considered to begin beyond the asteroid belt, but we shall not include the comets in this survey.

Cosmogonic Considerations

One of the major goals of the space program is to unravel the mysteries associated with the formation and evolution of the solar system. In most modern discussions of the formation of the solar system, it is assumed that the planets condensed from a fairly massive gaseous nebula, from which the sun may also have formed. It is assumed that this primitive solar nebula was much hotter near the central axis than far from the axis, either as a result of adiabatic compression of the gas to the higher densities encountered near the center or due to heating of the gas by the sun. From any such general scheme, basic thermodynamic considerations allow us to state some general expectations concerning the composition of the planets.

At temperatures between about 170° and 1800°K, metals, metal oxides, sulfides, and various silicates will be in condensed form in a gas of solar composition, and most of the remaining elements, being more volatile, will remain in gaseous form (*2*). These are the basic constituents of the inner planets and the asteroids. It is usually assumed that the meteorites which fall on the earth are fragments of asteroids; studies have been made of the trace element composition of meteorites, and the abundance variations have been interpreted as cosmothermometers and cosmobarometers (*3*). These studies indicate that the meteorites were assembled from their constituent particles at a temperature of about 450°K and a pressure of about 5×10^{-6} atmospheres. This already raises a puzzle in connection with Jupiter, which, if formed just beyond the asteroid belt, might also be expected to be essentially rocky in composition, with no significant content of the volatile light elements.

These more volatile light elements, present in the nebula as methane, ammonia, and water, condense at temperatures below 170°K. That temperature is the point at which ice condenses at the indicated low gas pressure. Ammonia condenses as a compound with water at about 110°K, and methane as a clathrate compound with water at about 60°K. Thus, as one progresses outward in the solar system, one might expect planetary bodies collected from chemically condensed species to consist first of rock, in the vicinity of Jupiter; then of rock plus water ice; then of the latter composition together with ammonia; and finally of rock, water ice, ammonia, and methane (*4*). Indeed, the two large outer planets Uranus and Neptune seem to have mostly a composition of rock plus ices, to judge from their rather low densities of about 1.2 and 1.6 grams per cubic centimeter.

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However, a significant fraction of the mass of these planets is in the form of hydrogen, and presumably of helium.

By contrast, Jupiter and Saturn are predominantly composed of hydrogen and helium. In each of these planets the ratio of methane to hydrogen has approximately the solar value (*5*).

Thus we find ourselves facing a major cosmogonic problem: Why does the basic character of the solar system change beyond the asteroid belt? Why did gas giants form in the outer solar system but not in the inner?

One suggestion, based on the similarity of the composition of Jupiter to that of the sun, is that a large-scale gravitational instability occurred in the solar nebula to form the planet Jupiter (*6*). This suggestion faces many difficulties. In a massive rotating gaseous disk, large-scale instabilities grow faster than small-scale ones (*7*), so one might expect most of the gas in the disk to be gathered together into a single object in the outer solar system, much more massive than Jupiter. Perhaps this is the way some binary star systems are formed. This mechanism, in any case, could not apply to the remainder of the outer planets. There appears to be a progressive departure from solar composition as one goes from Jupiter to Neptune, with hydrogen and helium probably forming only a minority of the mass in Neptune. If one supposes that the four giant planets were formed by a process of gravitational instability, with the ices settling toward the center and the bulk of the hydrogen and helium being removed by the solar wind, then one would be faced with the problem of explaining why such a mechanism should be so successful for Uranus and Neptune, and not for Jupiter, which is much closer to the sun and is subjected to a much higher flux of plasma in the solar wind (*8*).

Many attempts have been made in recent years to construct numerical models of Jupiter and Saturn, under the assumption that these planets are composed essentially only of hydrogen and helium. The most recent of such models, constructed by Hubbard (*9*), indicates that Jupiter should contain approximately 40 percent helium by mass (twice the solar content), and that the planet should be fully convective in the interior in order to transport heat to the surface, where it has been observed to be emitted at a rate considerably in excess of reradiated sunlight. The resulting model planet of Jupiter tends to be very hot in the central region 7,000° to 10,000°K. Smoluchowski (*10*) suggested that large-scale phase separations of hydrogen and helium may occur in the interior of Jupiter, but such phase separations would appear to require central temperatures less than about 3500°K. Thus, basic issues concerning the interior structure of the planet depend on an accurate determination of the central temperature. Models of Saturn constructed by these techniques contain an even higher mass fraction of helium, but no such model has ever been fully satisfactory in fitting accurately the mass, radius, and two gravitational moments of the mass distribution of the planet.

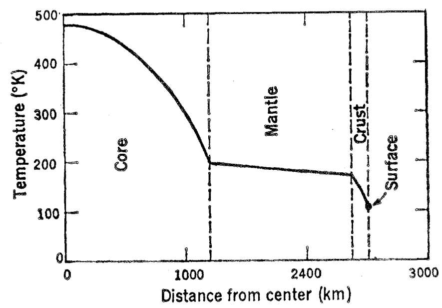


Fig. 1. Approximate temperature profile in any icy satellite the size of Ganymede, as computed by Lewis (*16*).

If such models should be basically correct, they raise another important cosmogonic question: If such a large-scale separation of hydrogen from helium has occurred in Jupiter and Saturn, under what circumstances did it take place? If the process were one of diffusive separation, with removal of hydrogen from the top of the planetary atmosphere by thermal evaporation or interaction with the solar wind, then a fantastically long time would have been required; it appears that such processes are not important at the present time. If the separation took place in the presence of a much smaller gravitational field, where thermal escape of hydrogen relative to helium might have been possible, then it is not clear how the gaseous system could be maintained in a configuration having such a low gravitational field for a long period of time.

Another approach to outer planet model building has been taken by Podolak (*11*). He has imposed the requirement that the ratio of hydrogen to helium in Jupiter and Saturn should be about the same as that in the sun, about 12/1. He has found that Jupiter then requires a rocky core containing several tens of earth masses of material, and an even higher interior temperature than that found by Hubbard. In the case of Saturn, he has found that a rocky core containing some ten earth masses is still required, together with two to three times this mass of water, distributed throughout the envelope. These results are quite consistent with a mechanism in which very large planetary cores of condensed material accumulated first, and these then produced gravitational capture of a large amount of the surrounding hydrogen and helium in the solar nebula. This also poses a problem: Why should such large planetary cores form in the positions of Jupiter and Saturn in the primitive solar nebula, while such accumulation was extremely inefficient in the asteroid belt? A possible answer to this question has been given by Cameron and Pine (*12*), who found in their models of the primitive solar nebula that a convection zone exists in the region of the inner planets, extending to the region of formation of the asteroid belt, which renders the processes of planetary accumulation much less efficient than should be the case farther out in the solar system.

These cosmogonic considerations show the primary importance of certain types of measurements in missions to the outer planets. A measurement of the ratio of hydrogen to helium in the outer planets is needed. This ratio can be determined approximately by remote sensing to a sufficient atmospheric depth from flybys, and much more accurately with an entry probe which penetrates deeply enough into the atmosphere to be within the region of convective mixing, below the "turbopause" level. Much more information is desirable on the content of rocky and icy materials in the planetary interiors; the water content of the interior is not readily apparent at the surface because the water will condense out in clouds at a much lower level than the observed cloud deck on Jupiter and Saturn, which is due to ammonia. A determination of this rocky and icy content requires a better knowledge of the distribution of density with radius in the planetary interior. The density distribution has an influence on the gravitational moments of the mass distribution, which can be measured with suitable accuracy by orbiting spacecraft (*13*). At the present time the first two gravitational moments are claimed to be known with reasonable precision only for Saturn, and even this claim may not be true (*14*); the second moment of Jupiter is uncertain within a range of a factor of 4, and even the first moments are exceptionally poorly known for Uranus and Neptune (*5*).

The issue of the central temperature of the planet can, in principle, be resolved if one knows that the planet must be convective in the interior and is able to measure the entropy of the gas in the outermost convecting region of the atmosphere (*15*). Such a determination requires a measurement of the temperature and pressure at the same point in the atmosphere. This can be done approximately by remote sensing and accurately with an entry probe.

The above three types of measurements demonstrate the utility of having different types of spacecraft missions. The early flybys (spinning and three-axis stabilized) will provide the basic environmental and exploratory data required for subsequent orbiter and probe missions. They set the stage for the efficient design of precision measurements for the probes and orbiters.

Satellites of the Outer Planets

The four giant planets are accompanied by a multitude of satellites. Most of them are probably wholly unlike any type of condensed body studied in the inner solar system. The larger and inner satellites of Jupiter, Saturn, and Uranus have very regular orbits, nearly circular, with a very regular increase in their spacing, and with some commensurabilities among the periods. These are the "regular" satellites. It is difficult to see how these regularities could have been produced unless these satellites were formed from flattened gaseous disks rotating around the planetary primary in much the same way that the planets seem to have been formed from a rotating gaseous disk which was the primitive solar nebula (*8*). In addition, the outer satellites of the giant planets are "irregular," tending to have fairly high orbital eccentricities, and some of the satellite motions are retrograde. These satellites were probably captured by the primary planets.

The masses and radii of these various satellites have been determined with useful accuracy only for the largest bodies, which are among the systems of regular satellites. These quantities are still sufficiently uncertain that the mean densities of the satellites are probably accurate to only a few tens of percent, but nevertheless the values are of considerable cosmogonic interest.

The density of typical rocky material, as represented for example by a stone meteorite, is about 3.7 g/cm^3. The densities of the major outer satellites are considerably less. The densities of the major Jovian satellites (*4*), in increasing order of distance from the primary, are 2.8 (Io), 2.6 (Europa), 1.6 (Ganymede), and 1.5 (Callisto) g/cm^3. The density of Titan, the largest satellite of Saturn, is 2.0 g/cm^3. The other satellite densities are too poorly known to be useful.

With densities as small as this the satellites must have a great deal of icy material in addition to rocky material (*4*). The inclusion of such a large amount of icy material is consistent with the formation of the satellites at large distances from the sun; the relative amounts of ice and rock that went into a particular satellite would also depend strongly on the thermodynamic conditions in the subdisks from which these regular satellites formed. It is not surprising that there should be a smaller amount of ice in the satellites closer to Jupiter, since the gaseous disk surrounding Jupiter from which the satellites formed would likely have had a lower density and therefore a lower temperature at greater distances from the primary about which it revolved.

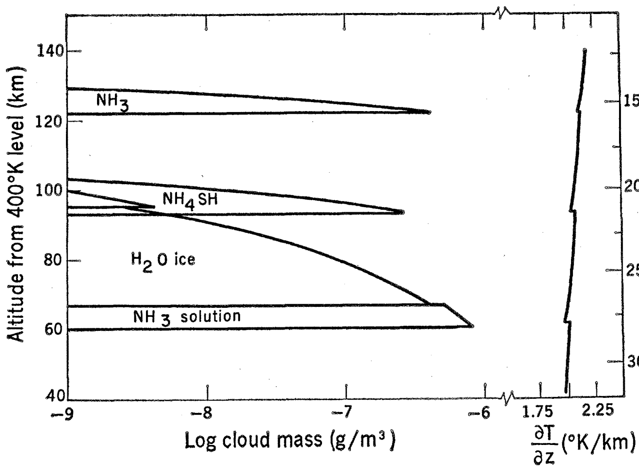
The lower density satellites may contain condensed ammonia as well as water. Such a satellite can have a fascinating internal structure, as shown by Lewis (*16, 17*). Ammonia and water form a eutectic mixture with a melting temperature of 173°K, which is only just above the daytime surface temperature of Callisto, the Jovian satellite which is the best candidate for this situation. The interior of such a satellite should be at a higher temperature than the surface owing to radioactive heating. This heating will melt and differentiate the eutectic mixture. Thus such a satellite should have an icy crust, a deep ammonia-water solution mantle, and a rocky core. A detailed thermal and structural model for a satellite of this type with the mass and radius of Ganymede has been constructed by Lewis (*16*), and is shown in Fig. 1. A satellite of this type is a wholly new class of object, never studied in detail in the solar system. Will craters formed in the icy crust become deformed by icy creep? Will rocky material deposited on the surface sink out of sight? Will major cracks form in the crust (*18*)? All these phenomena should take place in very different ways than might be expected in a rocky satellite. Television imaging of these satellites from spacecraft cannot fail to lead to some remarkably interesting discoveries. Such imaging will also have the by-product of giving us better satellite radii, and, hence, better mean densities.

Titan, the largest satellite of Saturn, has a remarkable atmosphere; it is the only satellite known to have one. The main constituent of the atmosphere appears to be methane, although there is a tentative detection of hydrogen (*5, 19*). Trafton (*20*) has determined the atmospheric pressure to be at least 70 millibars, and perhaps even as much as 1 atm. Polarization measurements indicate that clouds are probably present, and the existence of a fairly high-infrared brightness temperature of about 145°K indicates that a substantial greenhouse effect may exist in the atmosphere (*21*). This atmosphere may be a laboratory for organic chemistry, a place to study prebiological organic evolution (*4*).

These fascinating properties have placed Titan high on everybody's list of desirable objects to be examined by a flyby spacecraft. A radio occultation measurement made as the spacecraft passes behind the satellite from the direction of the earth should give valuable information about the atmosphere, and pictures of the surface and clouds may contain some interesting surprises.

Another prime objective for a flyby in the Saturn system is a study of the rings around the planet. The rings are composed of a swarm of particles orbiting individually about Saturn, and it appears that ice is a major constituent of these particles. There has been much argument about the size of the particles, suggested diameters ranging from a few micrometers to a few hundred meters (*5*). In the latter case the mass of the rings would be quite large, and this could have dynamic effects on the motions of the satellites of Saturn and on the determination of the gravitational moments of the planet. Imaging from a spacecraft should improve our knowledge of the density distribution in the rings and may detect organized motions such as waves if they exist; this information should help to clarify the above questions.

It is perhaps not surprising that a swarm of small condensed bodies could be left in orbit about a planet such as Saturn when the gaseous subdisk from which the regular satellites also formed was dissipated. At the distance of Saturn from the sun an icy body is stable against thermal evaporation, but this is not true at the distance of Jupiter. This can readily account for the absence of



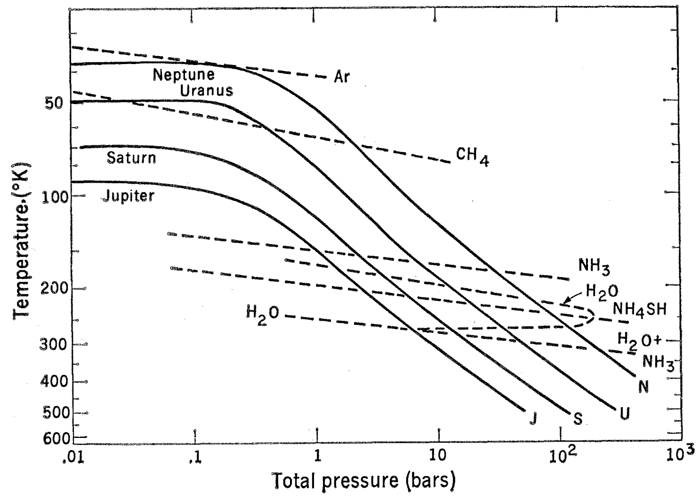


Fig. 2 (left). Cloud layers expected to form in the Jovian atmosphere if it has solar composition, computed by Lewis (*4*). The temperature gradient is shown on the right-hand side. Fig. 3 (right). Models of the atmospheres of the outer planets, with assumption of solar composition, and cloud condensation conditions, computed by Prinn and Lewis (*24*).

a swarm of icy particles in rings about Jupiter, but can we be sure that there is not a swarm of small rocky particles forming an undetected ring about Jupiter? If there is, it must have a very low surface density. Perhaps more to the point, why does Uranus not have a prominent set of rings, since ice is also stable at the distance of Uranus from the sun? Uranus also has a system of regular satellites, presumably formed from a rotating gaseous subdisk, and hence one might expect that a residual set of rings of small particles could be left in orbit inside the Roche limit of Uranus. The apparent lack of rings about Jupiter and Uranus makes the rings of Saturn all the more interesting to investigate, for it is important to know why this aspect of Saturn should represent such a cosmogonic special case.

Atmospheric Structure and Dynamics

The exploration of the outer solar system will provide a welcome opportunity to improve our understanding of the structure and dynamics of planetary atmospheres. This cannot fail to improve our theoretical understanding of our own atmosphere, a matter of considerable economic importance to us. Atmospheric motions are highly nonlinear and are very sensitive to boundary conditions. It is proving to be very difficult to simulate these motions in sufficient detail in computers or laboratory experiments. The planets represent vast natural laboratories with atmospheres in many different natural states under greatly different conditions. Only if we can understand these differences quantitatively can we acquire confidence in our ability to predict the behavior of our own atmosphere. Dynamic studies complement the measurement of structure at a single location, for advective heat flows play a dominant role in determining the local energy balance. Even the aeronomy of the upper atmosphere is important, for the selective absorption of solar wavelengths determines much of the atmospheric structure and helps to govern the manner in which the atmosphere evolves.

The atmospheres of the outer planets can be expected to have a variety of cloud decks. A mass of gas rising from a low level in the atmosphere, where it is warm, may contain as major condensable substances water, hydrogen sulfide, ammonia, and methane. Figure 2 shows the sequence in which these substances will condense to form clouds in the rising gas mass in a model atmosphere of Jupiter, assumed to be of solar composition as computed by Lewis (*22*). The first condensate, starting from the lower level in the atmosphere, consists of small droplets of ammonia solution in water. Above this is a layer of small ice particles. Farther up, the hydrogen sulfide combines with ammonia to form small particles of solid ammonium hydrosulfide, NH_4SH. Finally, the topmost cloud deck, which forms the visible surface of the planet, consists of small particles of solid ammonia. The visible colors of the Jovian surface may be associated with the chemistry and photochemistry of the NH_4SH layer and its various associated particles (*23*).

These concepts are generalized for the four giant planets in the manner shown in Fig. 3. Here model atmospheres of the four giant planets are shown as solid lines, and the condensation thresholds for various substances are shown as dashed lines (*24*). Cloud layers will be formed when one of the solid lines passes across a dashed line. Thus, it may be seen that methane clouds can be expected on Uranus and Neptune, but not on Jupiter and Saturn, in accord with observation. It may even be possible for argon clouds to form in some locations in the atmosphere of Neptune. Of course, the cloud layers would be much thicker in the event that certain of these condensable substances have greatly enhanced abundances compared to the solar mixture.

The ionospheres and upper atmospheres of the outer planets are of interest because they represent a new regime of photochemistry, which will influence the long-term evolution of the atmospheres. In the inner solar system, the earth has an upper atmosphere dominated by oxygen and nitrogen, while Venus and Mars have upper atmospheres dominated by carbon dioxide. The outer planets will have atmospheres dominated by hydrogen and helium. It has been predicted (*25, 26*) and confirmed (*27*) that the temperatures in the upper atmosphere associated with hydrogen and helium will be much lower than in the case of the inner terrestrial planets. However, in the outer planets there may be new heat sources, such as dissipation of mechanical wave motions in the upper atmosphere.

In one respect, Jupiter and Saturn behave more like the sun than like planets. This is in connection with the differential rotation of the atmosphere;

the equatorial region spins around the central axis considerably faster than do the polar regions (*5*). The planets are observed to have a banded structure, with narrow strips of latitude having different markings and being subject to considerable wind shear. Stone (*28*) has suggested that these zonal winds are driven by thermal energy sources, and that they represent a balance between a north-south temperature difference and the Coriolis force in the atmosphere. The local heat source may be due to water condensation below the visible atmospheric surface (*29*). Hess and Panofsky (*30*) have suggested that the light zones represent regions of rising gas, with condensation to form clouds, which give a higher planetary albedo in that location and have an anticyclonic vorticity. The dark zones would then be regions where the gas is sinking, subject to cyclonic vorticity.

The meteorology to be expected in the giant planets represents an interesting challenge to the atmospheric scientists. Various types of instability have been suggested for the atmosphere of Jupiter, and these may give rise to motions superposed on the zonal winds. Ingersoll and Cuzzi (*31*) have suggested that barotropic instability may occur, giving three-dimensional motions which feed on horizontal shear in the zonal flow and draw kinetic energy by horizontal eddy stresses. On Jupiter the horizontal scale length of this instability would be about 10° of arc on the surface, or about 10^4 kilometers.

Stone (*28*) has suggested the possible presence of baroclinic instabilities, which are three-dimensional motions drawing energy from the potential energy of the horizontal temperature gradients; such instabilities form mid-latitude cyclones and anticyclones on the earth. The horizontal scale length on Jupiter would be about one-tenth of that for the barotropic instability.

Stone (*28, 32*) has also suggested the presence of inertial instabilities, which are oscillatory motions with a time scale of some hours, drawing kinetic energy from vertical eddy stresses in the zonal flow. Here again the horizontal scale length would be about 10^4 km on Jupiter and the instability would be independent of longitude.

Superposed on these possible motions, one can expect convection to exist (*33*). If this should be vigorous, then the motions would be three-dimensional, having a scale length comparable to the scale height of the atmosphere, a few kilometers on Jupiter. The horizontal scale length would be reduced if the convection is weak.

There exists an equatorial current on Jupiter having a half-width of some 4° in latitude, which can be understood from scaling analysis according to Hide (*34*). There has been some controversy over the generation of this equatorial current, both inertial and baroclinic instabilities having been suggested (*33*).

The Great Red Spot on Jupiter has been an intriguing mystery for many years. It is evidently some sort of static phenomenon in the atmosphere, since gas is observed to divide and go around the edge of the Spot. It has been suggested that the Spot represents a stationary column of gas above some sort of irregularity, an elevation or depression, in the underlying topography of the planet (*35*). However, there are numerous objections to this hypothesis, among the most prominent of which are the facts that it is difficult for a Taylor column to exist in an atmosphere as unstable as that of Jupiter, and that the Red Spot has been observed to wander in longitude on the planet (*25*). This is obviously one of the locations to be closely studied in the detailed imaging of the planet.

One of the major interesting differences between Saturn and Jupiter is that the atmospheric zonal motions appear to be much stronger on Saturn than on Jupiter, at least in the region of the equatorial jet (*33*). This will produce obvious differences in any instabilities which draw energy from these zonal motions, but the same types of instability would also be candidates in the atmosphere of Saturn.

The atmosphere of Uranus is expected to be somewhat more stable, since there is no evidence for an internal heat source superposed on the reradiation of incident solar radiation. Furthermore, Uranus may not have pronounced zonal symmetries, and in that respect it may be more like the earth (*33*).

In order to settle these questions, various types of remote sensing are needed for these planetary atmospheres. Of primary importance are pictures taken close to the planet, which should not only allow the measurement of wind speeds, but may also allow an analysis to be made from the cloud patterns of various possible symmetries in the flows. The horizontal resolution of the pictures should be somewhat better than the vertical scale height of the atmosphere, in order that convective motions can be distinguished.

Planetary Magnetism

Among the planets in the outer solar system, the only one for which we have evidence of a magnetic field is Jupiter. The evidence arises from ground-based observations of its nonthermal radio radiation. The first evidence for this was from the circular polarization of the low-frequency plasma radiation. More extensive evidence resulted from studies of the synchrotron emission from energetic electrons spiraling in the Jovian magnetic field. From this it has been deduced that the axis of the magnetic field is tilted with respect to the planetary spin axis by some 8°, and an equivalent point dipole may be offset from the center of the planet by about one-tenth of the Jovian radius (*36*). The magnetic moment of Jupiter estimated by Warwick (*37*) is about 4×10^{30} gauss cm^3, which is some 5×10^4 greater than that of the earth. There is little evidence for radiating magnetospheres associated with the other outer planets; in the case of Saturn, the upper limit on similar nonthermal radio emission from the planet is only 1 percent of that of Jupiter (*5*). There has been considerable discussion as to whether this upper limit arises from a reduction in the planetary magnetic dipole moment or from the absence of substantial fluxes of energetic electons in the magnetosphere.

Planetary magnetism is generally thought to originate in the operation of a self-excited magnetic dynamo in the core of a planet (*38*). This represents a horribly nonlinear problem in physics, since the equations of electromagnetism must be coupled to those of fluid dynamics. However, it has become clear that a turbulent, electrically conducting core is needed, together with a reasonably rapid rate of planetary rotation. Nonuniform rotation of the fluid produces from the dipole field a strong toroidal field. In its turn, the dipole field is probably generated by the interaction of cyclonic convection with the toroidal field. The dipole lines up with the rotation axis, except for the irregularities in the convection.

The mechanism for generation of the Jovian magnetic field must be closely coupled to the properties of the core of the planet, and hence to problems of cosmogony. At pressures above about 2.8 megabars (*39*), such as those which exist in the deep interior of Jupiter, hydrogen undergoes a phase transformation to a metallic form, which can be fluid or solid, and the metallic hydro-

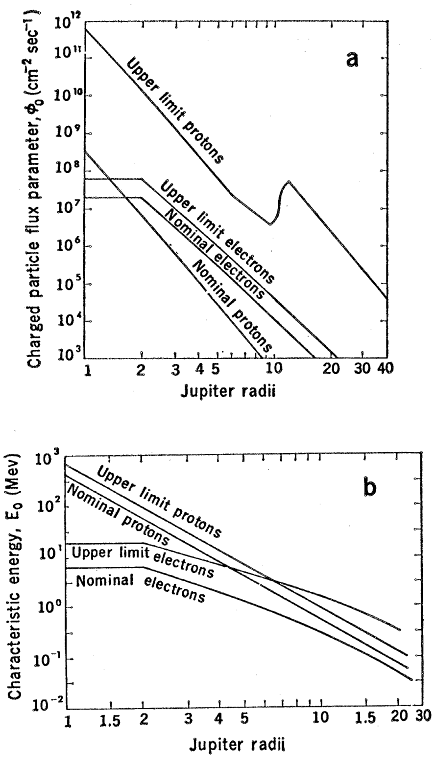


Fig. 4. Nominal and extreme proton and electron fluxes (a) and characteristic energies (b) in the Jovian atmosphere, adopted by the JPL workshop.

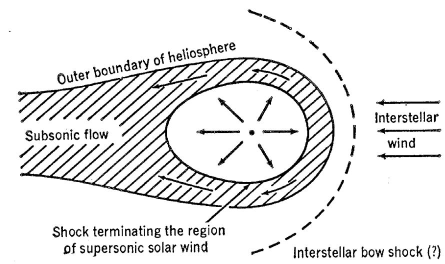
gen is expected to be electrically conducting (*15*). On the other hand, if Jupiter possesses a rocky core containing several tens of earth masses, presumably with a metallic iron core of its own, then this metallic iron core may be very much greater than that in the earth, giving Jupiter a very much stronger magnetic field than the earth, according to dynamo theory. However, at the lower temperature at which Jupiter was probably assembled, the equilibrium form of iron is in iron oxides (*2*), and these are unlikely to form a suitably electrically conducting core if they constitute the main bulk of the innermost core of Jupiter, unless they have had an opportunity to undergo an interaction with hydrogen at a higher temperature after being accreted into the growing Jovian planet. Even with a rocky core containing several tens of earth masses, there should be an extensive zone of metallic hydrogen surrounding the core, so that remains a candidate for the seat of generation of the magnetic field in any case.

In the case of Saturn, it is probable that metallic hydrogen has formed at the center, although the central pressure is considerably less than that in Jupiter. Any rocky core existing within Saturn may be much more massive than the earth, but it is certainly much less massive than that of Jupiter. On these grounds one could expect that the magnetic dipole moment of Saturn should be considerably less than that of Jupiter, which is in accord with observation.

It is probable that no metallic hydrogen can exist in the interiors of Uranus and Neptune, and the degree to which material in the cores of those planets may be electrically conducting is entirely speculative. Much interest will therefore attach to the measurement of the magnetic properties of these planets.

Over the years there has been much discussion about possible mechanisms which may be responsible for having produced the energetic particles within the terrestrial magnetosphere. Some of this discussion still continues. Because of the great uncertainties in our knowledge of terrestrial magnetospheric physics, it is particularly dangerous for the theoretician to attempt to predict the character of the energetic particles in the magnetospheres of Jupiter or the other outer planets. Only one of the mechanisms for production of energetic particles in the earth's magnetosphere, radial diffusion, can be scaled from the magnetosphere of the earth to that of Jupiter, and even in that case it is doubtful that the diffusion rate can be approximately scaled. It is entirely possible that other plasma processes will prove unexpectedly effective in populating the Jovian magnetosphere with energetic particles. Most of these points can only be cleared up by means of measurements made in the vicinity of the planet. Nevertheless, Kennel (*40*) has given a useful discussion of what the Jovian magnetosphere may be like if one scales the radial diffusion of particles to the Jovian magnetosphere.

This procedure has suggested that the Jovian magnetosphere may be quite different from the terrestrial one. In the terrestrial magnetosphere, convection of magnetic lines of force from one part of the magnetosphere to the other is very important, and is associated with auroral precipitation. Such convection should be relatively unimportant in Jupiter, where the magnetosphere should predominantly corotate with the planet. But if this is the case, then particles from the solar wind can easily penetrate through a disturbed magnetopause at Jupiter and hence diffuse radially inward toward the planetary surface. These particles are expected to become considerably more energetic in the Jovian magnetosphere than in the terrestrial one.



As the energetic electrons diffuse radially inward, they will lose energy by synchrotron emission due to spiraling around the magnetic lines of force. The energetic protons suffer no such losses. This raises the possibility that very large fluxes of energetic protons may exist in the inner radiation belt of Jupiter. This has been of special concern in connection with the exploration of the planet; if the proton fluxes are too great, they may irreparably damage the instruments on any spacecraft flying through the inner magnetosphere. Because of this concern the Jupiter Radiation Belt Workshop was held in 1971 at JPL; mechanisms that may affect the population of energetic particles in the magnetosphere were discussed (*41*). Some measure of the uncertainties in this subject is afforded by Fig. 4, which shows two model proton and electron radiation belts adopted by this workshop. One of these is a nominal set of fluxes and energies as a function of radial distance; the other is an extremely high set of fluxes and energies, which are considered possible, although unlikely. It was recommended that instruments be designed, if possible, to survive passage through the worst set of fluxes, adopted for engineering purposes. It is a measure of the caution surrounding this subject that the worst proton fluxes are some three orders of magnitude greater than the nominal set. Our knowledge of Jovian magnetospheric physics will benefit greatly from the measurements planned for Pioneer 10 when it passes the planet at three times the planetary radius in December 1973.

One of the more interesting Jovian phenomena studied within the last few years is the correlation between radio bursts from Jupiter and the position of its satellite Io (*5*). It has become evident that there are strong interactions between the Jovian magnetosphere and Io, and these interactions may be quite general between the magnetospheres of the outer planets and their more massive satellites. Questions arise concerning the absorption of energetic particles by the satellites, as well as perturbations to the magnetic structure in the magnetosphere in the wakes of the more massive satellites. In addition, the rings of Saturn may be particularly effective absorbers of energetic particles in the magnetosphere of that planet. The radio bursts themselves represent the most intense emission process known in the universe, except for the pulsars, and there is no convincing theory for these emissions. Thus, flyby spacecraft passing close to the major satellites of the outer planets are of interest for measurements of particles and fields as well as for imaging the satellites themselves.

Outer Solar Wind

Any spacecraft on a mission to the outer planets traverses interesting regions of interplanetary space far away from the sun. Although the solar wind has been intensively studied in the vicinity of the earth for a number of years, its properties at large distances from the sun remain somewhat conjectural. Thus, plasma and energetic particle detectors and magnetometers should remain essential parts of the "cruise science."

As the sun moves through interstellar space, the solar wind which is continually expanding from the sun creates a cavity in the interstellar medium (*42*). Figure 5 is a schematic diagram of this situation, where the cavity created by the solar system in traversing the interstellar medium superficially resembles the impact of the solar wind on the magnetospheric cavity of the earth itself. If the solar motion is supersonic with respect to the local interstellar medium, then one may expect an interstellar bow shock to form, and the subsequent subsonic interstellar medium will flow around the heliosphere boundary. The solar wind plasma is ejected supersonically from the sun, but since this must eventually merge into the interstellar medium there must be another shock transition in which the solar wind is slowed to subsonic speeds with respect to the interstellar medium. This accounts for the main features shown in Fig. 5.

The shock that slows the solar wind with respect to the interstellar medium would ordinarily be expected to occur at the point where the momentum flux of the solar wind became equal to the pressure of the interstellar medium. This would be at a radial distance from the sun of the order of 100 astronomical units (A.U.). However, as pointed out by Axford (*42*), the region of the shock is probably brought into about 50 A.U. from the sun after one allows for the negative pressure gradients in the solar wind associated with the magnetic field curvature beyond the shock and the diffusion of low-energy cosmic rays, and the decrease of the solar wind flux due to charge exchange with the interstellar medium.

The proposed Mariner-Jupiter-Saturn mission is particularly interesting for the purpose of attempting to measure the heliosphere boundary region because the spacecraft, after encountering Saturn, are expected to head in the general direction of the solar apex, toward the closest distance of the interstellar medium bow shock. Any spacecraft that flies by Pluto in the next few years would also head in the same general direction. It would be valuable if such missions could attempt to determine whether there is modification in the flow parameters of the solar wind due to charge exchange with the interstellar medium. It would also be valuable if the Lyman-alpha instrumentation on board the spacecraft were designed to search for neutral hydrogen near the sun; such hydrogen clouds have already been observed (*43*) and are thought to have a hydrogen atom density of approximately 0.1 per cubic centimeter and a velocity toward the sun of about 20 kilometers per second.

Long before the spacecraft reaches the distances at which such measurements become meaningful, it should be able to settle some questions about the flow of the solar wind much closer to the sun. There has been some discussion concerning whether the flow of the solar wind at distances beyond 5 A.U. will become much more regular than it is near the earth. Probably the main feature of the solar wind near the earth is the irregularity observed in the flow due to variations in solar activity. Varying rates of coronal heating cause the solar wind to flow at different expansion velocities at different times, leading to the continual propagation of disturbances through the interplanetary medium. The major question is whether these disturbances become damped at distances of the order of 5 A.U. or whether they continue to propagate through the interplanetary medium to much greater distances (*44*). At 5 A.U. from the sun the interplanetary magnetic field has become wound into a fairly tight spiral, which impedes the radial conduction of heat in the interplanetary medium, and which could have a tendency to damp out the waves and disturbances propagating at different rates through the medium. Possibly some reconnection of magnetic flux between neighboring sectors of different polarity might also take place.

If the expansion of the solar wind beyond 5 A.U. were to become smooth and regular, then one might expect that interstellar cosmic rays would be able to propagate inward to about 5 A.U. without much loss of flux (*45*). They would then encounter strong magnetic irregularities, which would impede their further inward diffusion, and they would have to accomplish such inward diffusion against the expanding magnetic fields in the inner solar system. This is expected to decrease the energy of the cosmic rays greatly, and also to decrease the fluxes. These decreases in particle energies and fluxes are inferred from the variation in the flux of interstellar cosmic rays which occurs as a result of varying solar wind modulation during the 11-year solar cycle.

If the interstellar cosmic rays can penetrate essentially unimpeded to about 5 A.U., the orbit of Jupiter, then one might expect a quite significant radial gradient in the cosmic rays within this distance. It is therefore somewhat surprising that no certain evidence for such a radial gradient has been found in a number of spacecraft experiments; the results of these experiments have been somewhat contradictory (*46*). The most recent results, taken during the early part of the voyage of Pioneer 10, showed that there may be an increase of as much as 6 to 8 percent in the flux of low-energy cosmic rays (80 million to 1 billion electron volts) in the interval from 1 to 2 A.U. (*47*).

Most of our theoretical constructs concerning the properties of the outer solar system may prove to be grossly in error, so that measurements of the actual quantities will lead to fruitful new insights into the properties of an important part of our local universe.

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The Teenage Birth Control Dilemma and Public Opinion

Judith Blake

The rising rate of unwanted pregnancy among single teenagers in the United States is creating a dilemma for public policy. On the one hand, policymakers are being urged to bypass normative concerns about premarital sexual behavior and, in a pragmatic fashion, to attempt to prevent unwanted pregnancy among single minors by making birth control information and services available to them. On the other hand, officials are admonished that, despite high rates of teenage illegitimacy, abortion, and premaritally conceived legitimate births, government assistance (or, in many states, even legal tolerance) regarding birth control services for unmarried minors is not morally defensible. The pragmatic and normative positions have recently been juxtaposed on the national scene. Viewing the situation in practical terms, the Commission on Population Growth and the American Future recommended a birth control policy to lessen unwanted pregnancies among unmarried minors (*1*). Expressing normative concerns, President Nixon voiced disapproval of the commission's recommendation (*2*).

In its report to the President and Congress, the commission considered, as one of a great variety of problems, that of unwanted, illegitimate pregnancy among minors. The commission explicitly stated that it was not addressing itself to the normative issues relating to premarital sexual behavior among teenagers, but rather was concerned with preventing the consequences of such behavior—teenage pregnancy. In its own words (*1*, p. 189):

> The Commission is not addressing the moral questions involved in teenage sexual behavior. However, we are concerned with the complex issue of teenage pregnancy. Therefore, the Commission believes that young people must be given access to contraceptive information and services.
>
> *Toward the goal of reducing unwanted pregnancies and childbearing among the young, the Commission recommends that birth control information and services be made available to teenagers in appropriate facilities sensitive to their needs and concerns.*

When the report was presented to the President, he made only two specific comments—both in disagreement. One comment concerned the recommendation on abortion, and the other referred to the recommendation on birth control services for teenagers. In singling out the latter recommendation for disapproval, Nixon was clearly not addressing himself to the pragmatic problem of preventing unwanted teenage pregnancy. Rather, his normative statement concerned the preservation and strengthening of family relationships. He said (*2*), ". . . I also want to make it clear that I do not support the unrestricted distribution of family planning services and devices to minors. Such measures would do nothing to preserve and strengthen close family relationships."

With the spokesmen lined up openly on either side, one may well ask how the American public views the problem. Are adult Americans prepared to take the purely instrumental and practical point of view voiced by the population commission, accept the notion of the sexually active teenager, and set about protecting her from pregnancy? Or are their views closer to those of the Chief Executive? Have people changed their opinions over time? How much cleavage is there among us on this issue?

This article presents public views on the controversy. The data come primarily from questions I have inserted periodically between January 1969 and August 1972 in national surveys conducted by the Gallup Organization, Inc. The results reported here are part of a long-term project to collect and analyze (over closely spaced intervals) public

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