The Grand Tour of the Outer Planets

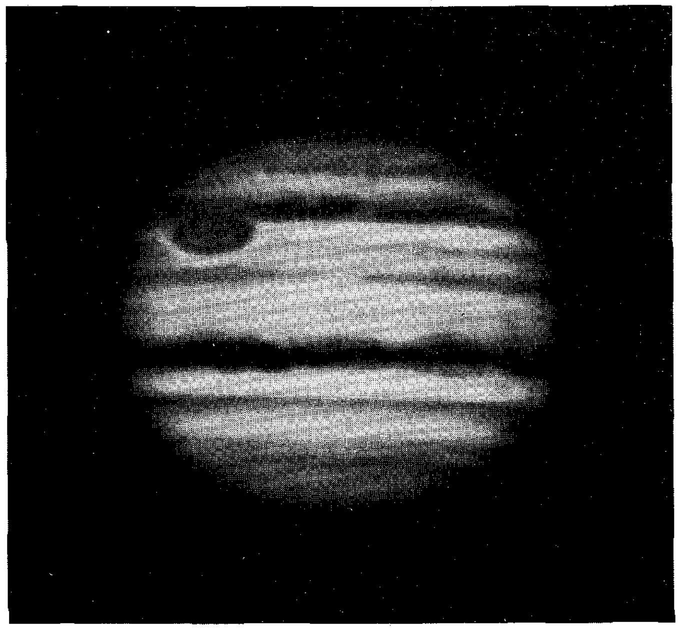
The planets will be uniquely aligned in 1976. The last time was when Thomas Jefferson was President. The next time will be in 2148.

All space missions flown to date have been from the earth to a single other body—the moon, Mars, or Venus. About nine years ago Caltech's Jet Propulsion Laboratory began studying space missions that might use the gravitational field of one planet to go to another planet, or out of the plane of the earth's orbit around the sun, or perhaps even to escape from the solar system. The first such mission is scheduled for 1973, when JPL will fly a spacecraft to Venus and then, using the gravitational field of that planet to change the speed and the direction of the spacecraft, on to the planet Mercury.

Back in 1965, Gary Flandro, a Caltech graduate student doing some work at JPL, was given the job of looking at various possible missions to the outer planets. He discovered that during the years 1976 to 1978 it would be possible to use Jupiter to go on to Saturn, use the field of Saturn to go on to Uranus, and use the field of Uranus to go on to Neptune. He dubbed this mission "The Grand Tour."

If we were to launch a Grand Tour from earth toward Jupiter in 1977, the spacecraft would arrive at Jupiter in 1979. Arriving there it would receive an increase in velocity of almost 11 kilometers per second and be deflected in its course by about 97 degrees to go on to Saturn, where it would arrive in 1980, then on to Uranus in 1984, then to Neptune in 1986.

But this all-in-one mission is hazardous because it requires passing very near to Saturn; Saturn's beautiful set of rings, composed of a multitude of small particles, could easily destroy the spacecraft. It would be more



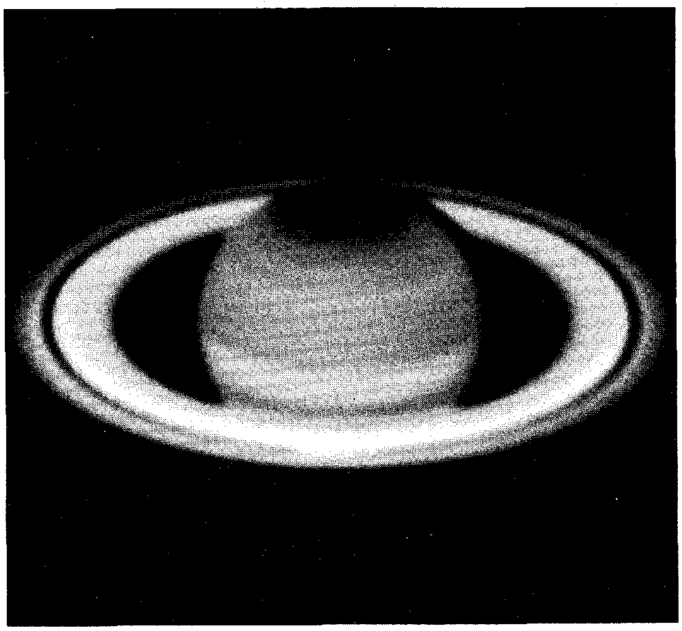
Jupiter: Are conditions under the clouds like those of a primitive earth?

prudent to send two spacecraft. The first one would go from earth in 1977 to Jupiter in 1979, to Saturn in 1980, and on out to Pluto in 1986. The second mission, launched in 1979, would go to Jupiter in 1981, Uranus in 1985, and Neptune in 1988. An interesting thing about the Saturn part of the mission is that although the velocity change is very small, the deflection angle, 25 degrees, is almost entirely up and out of the plane of the earth's orbit. Pluto is in a highly inclined orbit, and at the time of arrival in 1986, Pluto will be more than 1¼ billion kilometers above the main plane that most of the solar system lies in. Pluto also has an orbit of large eccentricity, and it can, when it is nearest the sun, come nearer the sun than Neptune ever gets. This is actually the situation at the arrival time in 1986.

This unique opportunity of flying from Jupiter to Uranus to Neptune depends on the relative positions of Uranus and Neptune. The last time this configuration of the planets existed, Thomas Jefferson was President of the United States; the next time will be in 2148.

Now, just the stunt of making a "four-cushion shot" is no reason to fly an expensive planetary mission. There are important scientific reasons for undertaking the Grand Tour.

by Ray Newburn



Saturn: How could the rings have survived for 5 billion years?

First, we want to know as much as possible about the origin and evolution of the solar system. Terrestrial planets like the earth have lost most of their lightest elements, and the earth has been differentiated so that what we see in the crust is, we think, very different from what is in the interior of the earth. But Jupiter, and perhaps Saturn, should contain almost all of the matter that originally went into their makeup when the planets were formed. In the case of Jupiter we deal with a planet about as near in composition to the material of the primordial nebula as we are likely to find in the solar system. Furthermore, that material may be well mixed so that a sample of the upper part of it may be representative of what the whole thing is made of.

Furthermore, to truly understand what the planets may have been like eons ago we need to know certain basic things about their structure today, and that structure can only be derived if we have certain basic facts such as size, density, composition, and energy balance. These facts can be found accurately (especially for Uranus, Neptune, and Pluto) only by visiting each of these planets.

A second major goal is to search for life on another planet, both to give more perspective to our own existence and to better understand the origin and evolution of life here on earth. We don't expect to find little green men running around on Jupiter and Saturn, but conditions on Jupiter and Saturn today are very like those conditions which most scientists think existed on the primitive earth several billion years ago when life may first have originated. Jupiter has a reducing atmosphere (one with no free oxygen in it) of hydrogen, methane, and ammonia. Although the temperatures we measure above the clouds are frigid, we know from radio observations that temperatures below the clouds are like those on earth today. And although we have never detected water spectroscopically on Jupiter (because it freezes out in the upper part of the atmosphere), there is every reason to think that most of the cosmic abundance of oxygen that we don't see may be trapped, together with hydrogen, in the form of water.

So the conditions below Jupiter's clouds today may be very like those that probably existed on the primitive earth; they are the exact conditions under which scientists in terrestrial laboratories have been able to produce amino acids—one of the fundamental building blocks of living matter. Of course, it may be that on Jupiter the atmosphere will be convective, mixing to such a depth that the heat far below may destroy these compounds. But even if that's true, there are regions—such as that of the great red spot—which may be stagnant and so may be a good place to look for the complex organic compounds that are precursors to life as we know it. And if Jupiter has no such good place, we can look on Saturn, which is very like Jupiter.

We know so little about Uranus and Neptune that we can't really say much about conditions there, but they too should be of some interest to the biologists.

A third major goal in the space program is to understand our own planet and its environment better. Much of the study of the weather and environmental pollution requires an understanding of atmospheric circulation and thermal balance. We can't very well simulate a whole planetary atmosphere and its large-scale effects in the

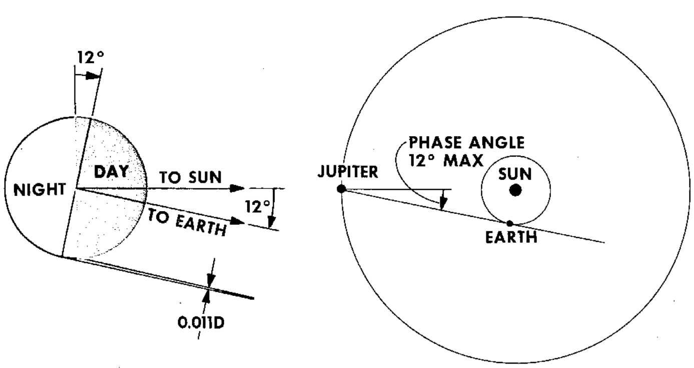
PLANETARY COMPARISONS

	MEAN SOLAR DISTANCE AU	EQUATORIAL DIAMETER EARTH = 1	MASS EARTH = 1	DENSITY g/cm^3	ROTATION PERIOD SIDEREAL	ATMOSPHERE MAJOR COMPONENTS
MERCURY	0.387	0.382	0.056	5.50	58.6d	None detected
VENUS	0.732	0.948	0.815	5.27	243.0d	CO_2 >90%
EARTH	1.496×10^8 km	6,378.16 km	5.97×10^{24} kg	5.52	23^h56^m	N_2, O_2
MARS	1.524	0.532	0 107	3.94	24^h37^m	CO_2 ~ 90%
JUPITER	5.203	11.19	317.9	1.33	9^h55^{m*}	H_2, He
SATURN	9.523	9.47	95.1	0.69	$10^h14^{m\dagger}$	H_2, He
URANUS	19.164	3.69 ?	14.5	~1.68	~10.8h	H_2, He
NEPTUNE	29.987	3.92	17.3	~1.59	~15.8h	H_2, He
PLUTO	39.37	~0.5	0.18 ?	~7.7 ?	6^d09^h	None detected

* SYSTEM III
† VISIBLE SPOTS AT EQUATOR

laboratory, so we really need other examples against which we can compare the predictions of our theories.

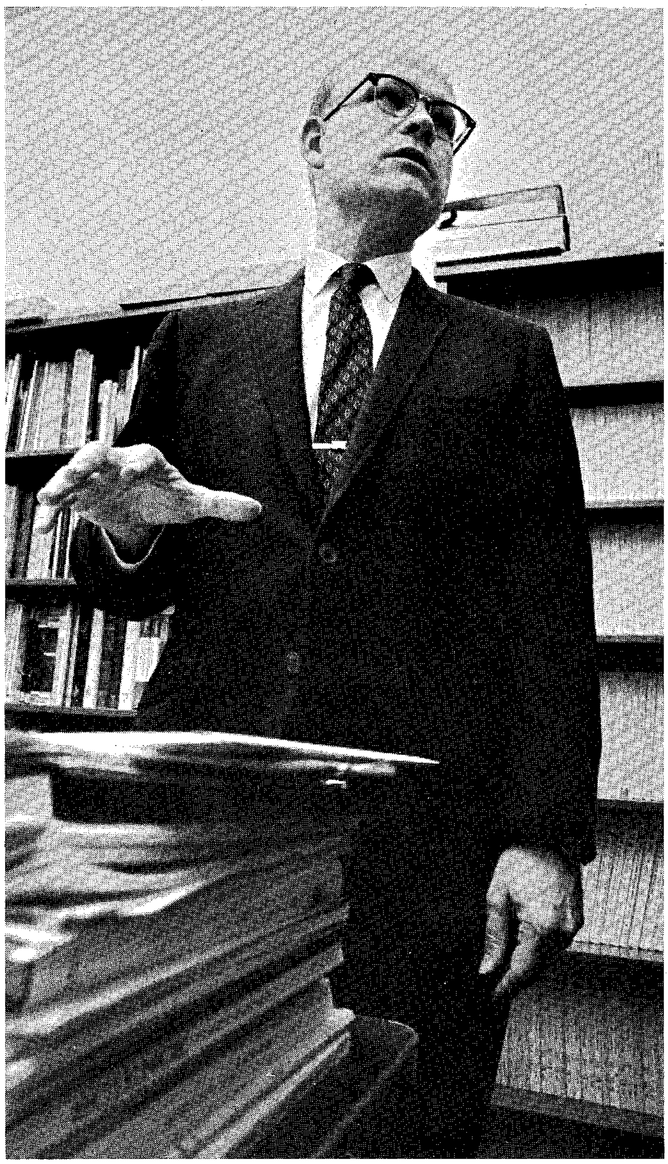
Now this may sound like a red herring to suggest that we can learn more about the earth by study of the outer planets, but that's not the case. Here on earth, for example, there is a mysterious ocean current (called the Cromwell current or the equatorial undercurrent) which flows about 400 kilometers wide and 300 meters thick in a westerly direction at the earth's equator in the Atlantic and Pacific Oceans. Oceanographers say that the question of what drives this Cromwell current is one of the most interesting unsolved problems in dynamic oceanography. Similarly, in the stratosphere above the equatorial region there are winds called the Berson Westerlies. They too are unexplained. On Jupiter and Saturn there are equatorial atmospheric jets that seem to be an exact analog of the peculiar currents in the earth's ocean and atmosphere. So there are close analogies between some of the dynamic things going on in outer planet atmospheres and things occurring on our own earth.



In looking at Jupiter from the earth, we can never see more than a sliver of its night side—far too little to permit understanding of the planet's energy balance.

The evolution of the solar system is a continuous process, although there have almost certainly been periods during which change was more rapid than at present. To understand the past, an accurate knowledge of the present is mandatory. Only by knowing "what is" can we use physical principles to imply "what was." The problem of the present structure of the planets is a complex one, requiring knowledge of composition, energy balance, and basic physical parameters, among other things. Yet, some of these parameters are known very poorly.

There are fundamental limitations, caused by the vast distances involved, on trying to do astronomy from the earth. For example, the equatorial diameter of Neptune is 3.92 that of the earth—about 50,000 kilometers. But in almost any astronomy textbook the value that's given is at least 10 percent less than that. In 1968 Neptune moved in front of a faint star, and by timing the passage of Neptune in front of it, astronomers made a more accurate measurement of the radius than had ever been made from earth before. Now, a 10-percent error in the size of a planet means a 30-percent error in the density of that planet. So while most textbooks give the mean density as about 2.3, we now think it is about 1.6. How can we possibly understand the planet when we don't even know the density of the material making it up? If the value of



JPL astronomer Ray Newburn

Neptune's radius was so far in error, that of Uranus may be equally poor.

Measurements made by a spacecraft can resolve such ambiguities. If we track a spacecraft as it passes behind each planet and time the disappearance and reappearance of the radio signal, we can get a measure of the planets' sizes. Obviously, in a planet with an atmosphere there are complications—such as refraction of the signal—but these can be accounted for. We may be able to find out something about the rotation periods of the farther planets if there happen to be markings on them and we take pictures over a period of time. We can also measure the flattening of planets, such as that obviously exhibited by Uranus; we have only the very crudest idea of how flat Uranus and Neptune really are. Neither mass nor radius are known with any accuracy for Pluto. The density of that peculiar body is uncertain by at least 50 percent.

How can we possibly understand a planet when we don't even know the density of the material making it up?

Another limitation of trying to do astronomy from earth is that the angle between the earth and sun as seen from Jupiter (the phase angle) is small, and in fact can never be more than 12 degrees. The angle is even smaller for planets more distant from the sun. Consequently, we can never see more than a sliver of the night side of *any* of the outer planets from earth. No telescope on earth or in orbit around the earth can overcome that geometric fact. Only a spacecraft flying outward can do so.

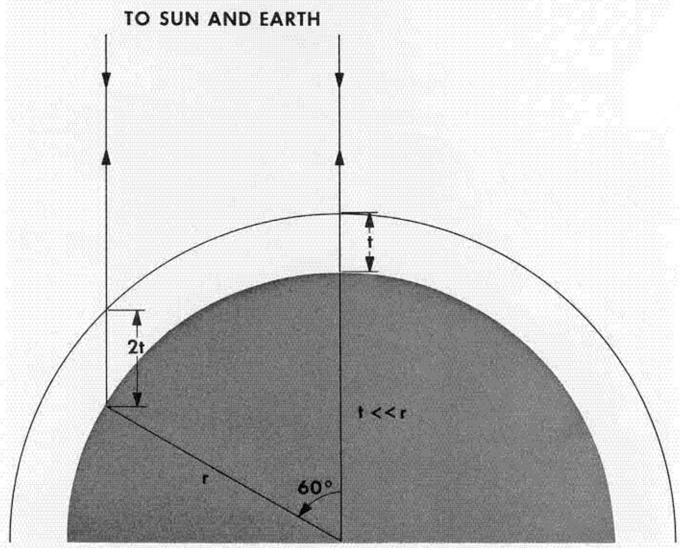
The inaccessible large-phase angles hold the key to quantitative understanding of the planetary energy balance. We know how much power the earth receives from the sun (the solar constant); the power from the sun that reaches other planets is reduced by the square of their relative distances. Part of that power is reflected, although the exact amount is uncertain because the part reflected at large angles cannot be seen from earth, and the remainder is absorbed.

If these outer planets are in equilibrium with the sun, we can equate the energy absorbed to the energy emitted and find out what the average temperature of the planet should be. But because we don't know how much energy is reflected or emitted from the parts of the planet we can't see, there is some uncertainty in the temperatures. When we measure temperatures on Jupiter or Saturn, they are higher than the temperatures we might expect no matter what we assume about their reflecting properties. Somehow, if we believe these figures, Jupiter is radiating 2.7 times more energy than it is receiving from the sun, and Saturn appears to be radiating about 3.5 times as much energy as it receives.

If this is true, then the classic descriptions of Jupiter and Saturn—a core of very cold, solid metallic hydrogen and helium; a surrounding region of nonmetallic solid hydrogen and helium; and an atmosphere of low conductivity—seem unlikely to be correct. A second possible picture of Jupiter, a modified classic picture, is the same except that the core is fluid. It still maintains some lattice structure, it is still metallic hydrogen and helium, but now the core material can move and can

The rotation period of Jupiter's great red spot has changed more or less continually during the last 100 years.

transport energy by convection. Instead of being cold, its temperature might be 10,000 degrees Kelvin. The excess energy observed could be the result of gravity causing the planet to collapse as little as one millimeter in a year, converting gravitational potential energy to thermal energy. Furthermore, the fluid conducting core, as it moves, might generate the magnetic field on Jupiter very much as it is thought that the earth generates its magnetic field.



If Jupiter's atmosphere were relatively simple, then a measurement of the abundance of constituents would vary according to the thickness of atmosphere being looked at, with the smallest amount at the center of the disk. But, in fact, all the measurements seem to be about the same.

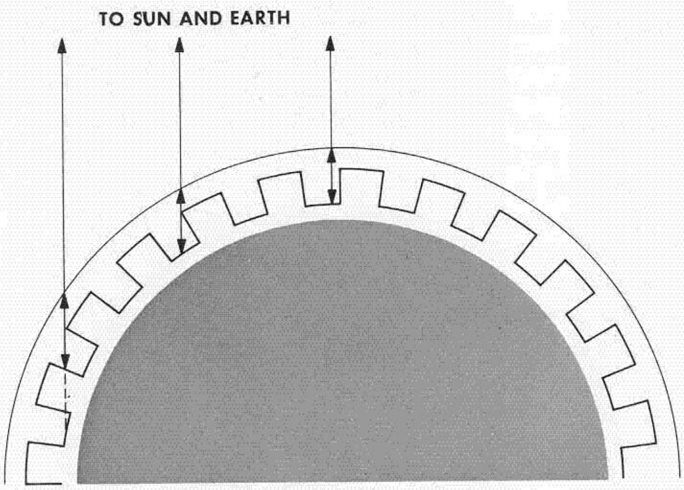
Two other interesting hypotheses about the structure of Jupiter are worth noting. The first is an idea of Raymond Hide, the deputy chief of the Meteorology Office in Great Britain. He suggests that perhaps the denser atmosphere below the clouds has sufficient conductivity to become a self-exciting dynamo and to generate the magnetic field. He further suggests that there could be energy storage within toroidal magnetic fields in that region and that these fields might store energy and later release it in a long-period cyclic process, thereby accounting for the present excess of power radiated. In this model the temperature of the interior could be low or high, although for other reasons Hide would prefer to have it hot enough for some fluid motion. Yet another hypothesis is that the planet is fluid throughout, having no solid surface, as calculations done by W. B. Hubbard at Caltech showed was possible.

Obviously, unless we know which of these or other models approaches the real Jupiter, we'll never have any idea of how the planet originated. If we can make radiometer measurements and find out if the energy imbalance is real and where the energy seems to be appearing, that will be one step. Another step would be to take a magnetometer to Jupiter and to measure its magnetic field. The origin of the field may be revealed by measurements of its detailed structure very near the planet. The same problem exists for Saturn, although to date it is not known whether Saturn even has a magnetic field; as for Uranus and Neptune, we don't know much about their thermal balance or anything about possible magnetic fields. It is unlikely, at least with any present instruments, that we will be able to determine these facts from the earth.

There is another quantity that is important if we are going to have a reasonable picture of these outer planets—and that is their composition. If we don't know it, then we don't know important structural parameters like specific heat, viscosity, opacity, conductivity. It may seem that the exact composition of these planets could be determined spectroscopically from earth, but so far this has not been possible.

The simplest model of a planet is that of a surface or cloud layer which reflects diffusely (like a perfect Lambert sphere) over which is a transparent atmosphere. The strength of the spectral lines (the record of how much light at a specific wavelength is absorbed by atoms or molecules in the atmosphere) is directly related to the number of atoms present in a planetary atmosphere. The thicker the atmosphere, the stronger the lines. For this simple model, a "look" toward the edge of the planet's disk sees a thicker atmosphere than one right at the center; for an ideal Jupiter we should see a spectral line near the edge that is twice as strong as the one near the middle. But, in fact, they are virtually the same. The model just doesn't work.

About 15 years ago Squires suggested that great cumulus clouds—like towering thunderheads on earth, though not made of water—might occur on Jupiter, complicating the atmospheric geometry. This is ingenious



One suggestion advanced to explain the anomalous measurements of Jupiter's atmosphere was that the base of the atmosphere was not the planet's spherical surface but the very uneven top surfaces of great cumulus clouds. But if that were the case, ammonia would freeze out of the atmosphere at the top of the clouds, leading to different relative abundances of ammonia and methane for different measurements. But the relative abundances of methane and ammonia are essentially the same in all measurements.

geometrically, but it does not solve the problem on Jupiter. For example, Jupiter has both methane and ammonia in its atmosphere. But ammonia freezes at temperatures that are present in the upper atmosphere of Jupiter, so up at the top of those clouds there shouldn't be any ammonia. Therefore, the relative abundances of methane and ammonia shouldn't seem to be the same at the center of the Jovian disk, where the bottoms between the towers are visible, and at the edge of the disk where only tower tops can be seen. But the apparent abundances are about the same, so that approach won't work either.

What we see when we look at Jupiter's atmosphere is probably the result of an inhomogeneous atmosphere, an atmosphere containing both molecules which absorb light and aerosols which scatter it, further complicated by the relative abundance of absorbers and scatterers changing with altitude. This creates a problem of great difficulty, both theoretically and observationally. We do know that Jupiter, because of its low density, is composed mostly of hydrogen and helium. Furthermore, in 1953, Jupiter occulted a star, and a crude measurement of the molecular weight of the atmosphere was obtained at Mt. Wilson—3.3. This led people to suggest that there was about the same amount of helium (molecular weight of 4) and molecular hydrogen (weight of 2). But it was a difficult measurement to make, complicated by noise because the star was faint and scattered light from Jupiter relatively large.

The observations were very important because they ruled out heavy gases as major atmospheric components, but they could support, equally well, pure molecular hydrogen or pure helium. Other (spectroscopic) observations since that time have convinced planetary astronomers that there is probably five to ten times as much hydrogen as helium; in fact, observations today are compatible with no helium at all. To better understand this situation we require extremely high-resolution spectral observations as well as a theory for inhomogeneous atmospheres. It is unlikely that the observations of Jupiter can be made with satisfactory accuracy from earth, and similiar observations of Saturn, Uranus, and Neptune seem impossible from earth with existing equipment.

We can actually create our own occultation, using the radio signals transmitted from spacecraft, however, and these signals do not have the noise problem of optical observations. Knowing something about the atmosphere already, we can find the relative abundance of hydrogen and helium in a fairly unambiguous fashion, especially if supporting temperature measurements are also made.

Another fascinating problem we face on the outer planets is that of differential atmospheric rotation. The equatorial region of Jupiter rotates at a higher rate than the rest of the planet. This System I region, which includes 10 degrees on either side of the equator, rotates in 9 hours and 50 minutes. System II, the high latitude regions, rotates in 9 hours and 55 minutes, so there is an equatorial jet on Jupiter moving about 225 miles an hour faster than the rest of the visible cloud surface of the planet. There is also a so-called System III determined by radio observation which is rather near to that of System II, but not identical. The System III period is most probably that of the bulk of material making up the body of Jupiter. Detailed imagery and thermal maps may help us to understand these complex dynamics.

One of the fascinating dynamical problems of Jupiter concerns the great red spot. Its rotation period apparently has changed more or less continually during the last 100 years. All of the early theories were that it floated in the atmosphere of Jupiter. We know now that the atmosphere of Jupiter is mostly hydrogen and, since there is nothing lighter than hydrogen, it can hardly be a floating island. Perhaps the best current explanation (due to Raymond

Iapetus, the ninth satellite of Saturn, varies in brightness by two magnitudes—a factor of six. How can that be?

Hide) is that it is a so-called Taylor column—a stagnant region formed as the thick, rapidly rotating atmosphere encounters and interacts with some topographic irregularity like a mountain range or large hole.

If the great red spot is such a column, how can it be rotating with a variable rate? Perhaps the period of rotation of Jupiter itself has changed, as matter is redistributed within the fluid interior of the planet. Or perhaps the planet is fluid throughout, and the irregularity is not a fixed mountain range but just the upper end of a great convection cell in the interior of the planet, or a magnetic loop within the dense, lower atmosphere. There are all kinds of theories, but very few answers. Close-up photographs might provide some.

Saturn also appears to have an equatorial jet like Jupiter. Near the equator the period of rotation appears to be about ½ hour less than the rotation in the higher latitude region. But the biggest dynamical problem of Saturn is its beautiful rings. They are known to be composed of a myriad of individual particles, because at times stars have been seen right through a ring and because the outer parts of the ring rotate more slowly than the inner parts. If those particles are not all in perfect circular orbits, then there must be collisions, which would tend to destroy the rings. Similarly, if there is any inclination among the various orbits, again there must tend to be collisions among the particles. Yet, gravitational perturbations by Jupiter and by Saturn's own satellites must tend to introduce such imperfections. It's difficult to understand how these rings could have survived such collisions for five billion years, yet it's equally difficult to understand how they might have been created more recently. We don't really understand the rings today. We don't know how big the particles are, and we don't know what the composition of the rings is, although there is some spectroscopic evidence that ice is present. We don't know how thick the rings are, though they can't be more than a few kilometers thick.

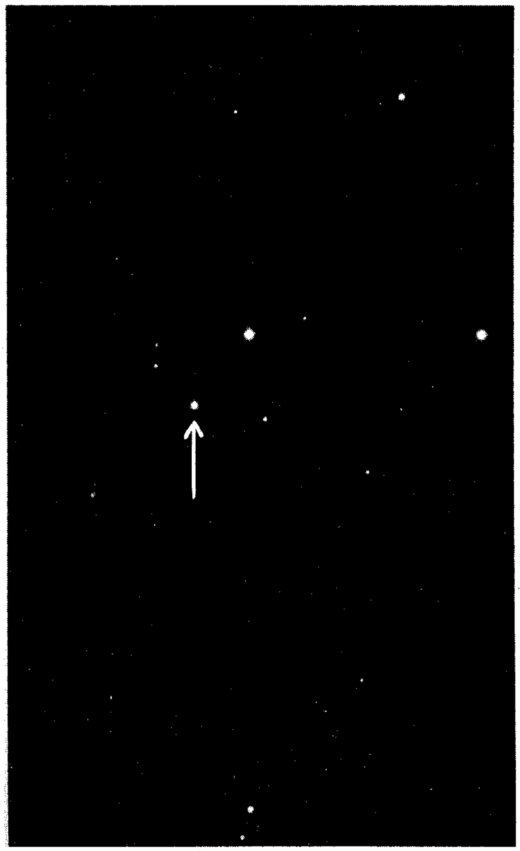
One of the difficulties in studying the rings is that the maximum viewing angle (sun-ring-earth) that can ever be achieved from earth is 6 degrees. If we can have a spacecraft observe the rings at different angles, studying brightness and polarization, we may learn something more about the particle size and distribution. Simple imagery should help to set an upper limit on the ring thickness.

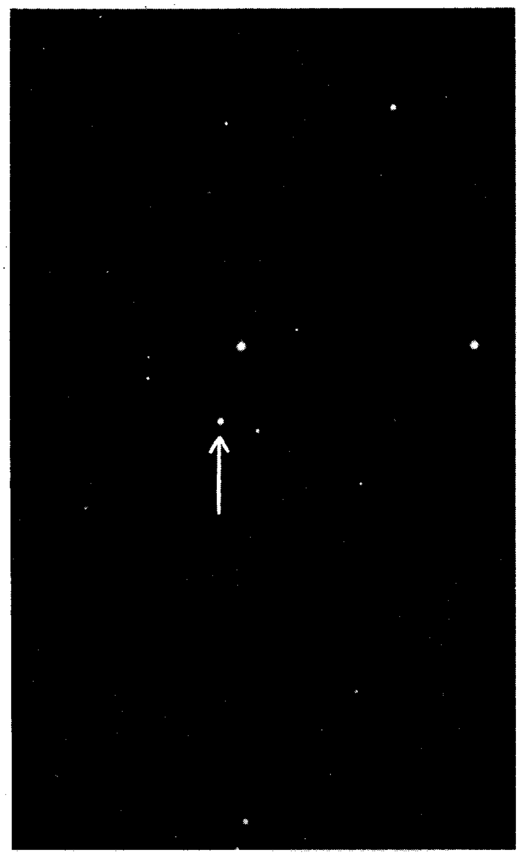
Uranus presents another unique situation. While most planets have their axes of rotation near the pole of the orbit of the planet (on earth the equator is inclined only 23½ degrees to our planet's orbit around the sun), Uranus is tipped completely over so that the axis of rotation of Uranus is almost in the plane of its orbit. How this orientation came about is one of the great mysteries of the solar system's formation. There should be some interesting atmospheric effects occurring on a planet which is heated at one pole, with the other pole in darkness for a quarter of the planet's 84-year period of revolution about the sun. A study of its behavior may teach us a great deal about atmospheric dynamics.

We can't say much about Neptune and Pluto; we just don't have enough data to know what the problems are there. It may be that Pluto is an escaped satellite of Neptune, a possibility first pointed out by Professor Raymond Lyttleton of Cambridge about 35 years ago. In fact, everything we know about Pluto indicates that it's almost identical to Triton, one of the two known satellites of Neptune.

The satellites of the outer planets are also worth more study. Jupiter's Ganymede is probably larger than the planet Mercury, so it is certainly not an insignificant body. And four of the 29 outer planet satellites—Callisto and Ganymede of Jupiter, Titan of Saturn, and Triton of Neptune—are bigger than our moon. Titan even has an atmosphere of methane.

One of the stranger satellites is Jupiter's Io. When it is observed coming out from behind Jupiter's shadow, it appears to be a bit brighter for about ten minutes than it was when going into eclipse; then it decays to the brightness it had before. *If these observations are correct,* the simplest explanation is that Io, too, has a bit of an atmosphere—perhaps methane or nitrogen. It might be that as Io falls into the shadow of Jupiter and gets colder, the atmosphere snows out on the surface, making the surface brighter. When Io reappears, it's brighter; but as it warms up in the sun, the atmosphere vaporizes again and Io goes back to normal.





Pluto: Is it an escaped moon of Neptune?

Io is peculiar in other ways too. It is distinctly orange, much redder than the other Jovian satellites, and the color changes as Io moves around in its orbit. Io also has very peculiar back-scattering properties—when we look at it, the energy falling on it comes almost straight back at us. Its retro-reflection properties are greater than those of any other natural body in the solar system. It would be extremely useful to get a series of pictures of this satellite at different angles and through different color filters.

There is another satellite in the solar system that is even more peculiar than Io. Iapetus, the ninth satellite of Saturn, is known to vary in brightness by two magnitudes—a factor of six—as it moves from one side of Saturn to the other. How can that be? One might even guess that Iapetus is brick-shaped and rotating at half the rate that it revolves about Saturn. But how can a body that is as big as Iapetus—perhaps 1,300 kilometers in mean diameter—be brick-shaped with a six-to-one aspect ratio? Known materials are unlikely to have sufficient strength to maintain that shape, six times as big in one dimension as any other, and this is almost certainly not the explanation. Neither have I yet accepted the explanation given in the book version of *2001* that Iapetus is a sort of cosmic transportation relay station. But one is *almost* forced to science fiction in trying to deal with the satellite. Apparently one hemisphere is simply six times as bright as the other. I would certainly like to get some pictures of Iapetus, and that's something the Grand Tour spacecraft might be fortunate enough to accomplish.

Although I have dwelt a great deal on Jupiter, that planet is not the real goal of the Grand Tour mission. We could launch to Jupiter about every 13 months from the earth. But to really understand the solar system, we need certain basic knowledge about *all* of its major bodies —things like accurate values for the density, the hydrogen and helium abundance, the energy balance, and magnetic field information for Uranus and Neptune that we can get only with spacecraft. We have a chance to do that with reasonable economy this decade; otherwise we must develop new vehicles with greater performance and spacecraft with very long lives, or wait until the middle of the 22nd century.