

Cosmic Chemistry: Planetary Diversity

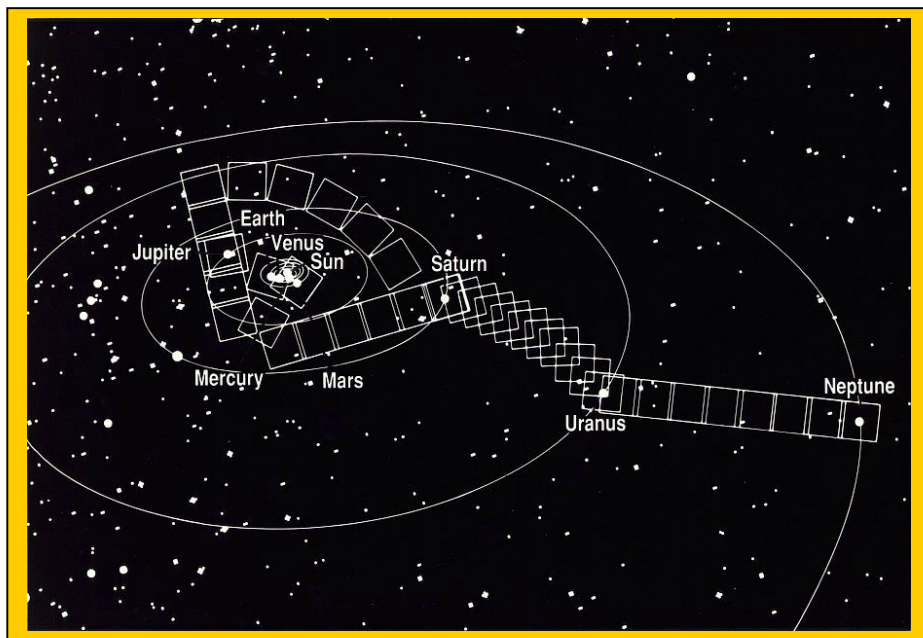
The Solar System or Do Nine Planets a Baseball Team Make?

APPENDIX A

INTRODUCTION

There are many ways to define the solar system. For instance, it might be sufficient for some purposes to define it as consisting of those objects subject to the sun's gravitational field. Or it might be defined in terms of the reach of the solar wind. In either case it would be clear that the solar system extends beyond the outermost planet. What is intended here is a discussion of what might best be called the central region of the solar system, the part that extends only out to the edge of the planetary system, which is what most individuals think of when the term solar system is mentioned.

This region of space is, to be sure, quite empty on the average. However, located in certain regions are many objects of fascination, study, and speculation. Most of these objects orbit around the sun in a plane close to the sun's equatorial plane, and they comprise only a small portion (less than 0.15 %) of the total mass of the solar system. The most massive and obvious of the solar system objects are the nine planets, which circle the sun in almost circular orbits ranging in radius from 0.4 AU to 40 AU (Note: 1 AU is the average distance from the sun to the Earth, 1.5×10^{11} meters). The diameters of these objects range enormously from a few thousand km to more than 100,000 km and some of them have orbiting satellites and encircling rings consisting of dust and ice. Some of the satellites are quite large, in some cases as large as the smallest of the planets!



The solar system: Note black lines for terrestrial

Between the orbits of Mars and Jupiter a large family of smaller bodies is found, having diameters ranging from a few hundreds of km. These asteroids also orbit the sun in roughly circular paths. Last, as unique solid objects, there are the comets, which are smaller yet and which move in elliptical orbits that usually are highly inclined relative to the plane of the Earth's orbit. Finally distributed throughout are micron-sized dust particles and the solar wind, a plasma consisting largely of electrons and protons.

In the remainder of this article, the planets will be discussed. This discussion will not be comprehensive or exhaustive because there are many excellent, well-illustrated books (see reference list) that present beautifully detailed descriptions of the planetary system. In this text, the goal is to present only selected, salient features of the planets, especially as they relate to planetary diversity.

It is convenient to organize one's thoughts about the solar system around the rocky, terrestrial inner planets (Mercury, Venus, Earth, and Mars) and the large, cold and gaseous outer planets (Jupiter, Saturn, Uranus, and Neptune). The ninth planet, Pluto, does not fit conveniently into either category and some workers in the field do not consider it to be a planet at all!

THE TERRESTRIAL PLANETS

Mercury



As the planet closest to the sun, Mercury is much more subject to the ravages of the fierce heat of the sun than the other planets and temperatures at the surface can reach as high as 700 Kelvins. The barren, pock-marked surface of the very small planet shows no evidence of recent erosion, volcanoes, or tectonic activity. In some ways Mercury can be regarded as a fossil left over from the earliest days of the solar system that has largely served only as a target for the various objects that have crashed into it.

As a terrestrial planet, Mercury was formed from large chunks of rock that fused together under the influence of each other's gravity, building up a more massive body with each fusion. The chunks of rock must have included highly refractory condensates from the nebular cloud, such as aluminum oxide, in addition to metals—largely iron. Toward the end of the formative period the last of these large chunks blasted out craters in the thin crust, beneath which the planet was molten. The molten interior was kept at temperatures high enough to melt iron by the energy released when the planet suffered collisions, as well as by the decay of radioactive atoms contained in the rocks. The molten iron percolated down into the interior to form a metallic core. During this time, tidal forces from the sun acting on the molten components resulted in the planet's changing its shape to a sphere, the thin crust cracking to

accommodate the changes. Lava may have welled up through the cracks and cooled to form the flat plains that now cover the majority of the planet's surface. Then some 3,850 million years ago a catastrophic collision with a large asteroid shook the entire planet to its core, sending out shock waves that rearranged the entire appearance. Subsequently the planet started to cool and settle down into a slightly shrunken, wrinkled, and cratered planet that has continued to be assaulted by a diminishing barrage of small rock fragments.

Of great interest is Mercury's density of 5.43 g cm^{-3} , which was measured accurately by Mariner 10 during three passes in the mid-70's. If we allow for the fact that Mercury is small with low compressional forces, the case can be made that it has the highest average density of any of the planets. Earth is often listed as having a higher density, but Earth is much larger than Mercury, and the average density is rendered artificially large by the compressional forces that compact the interior. The "uncompressed" densities of Mercury and Earth are about 5.3 and 4.45 g cm^{-3} , respectively. The high density of Mercury suggests that half or more of its volume consists of an iron core surrounded by lighter mantle and surface rocks. Measurements of Mercury's magnetism by Mariner are consistent with this view.

Since Mercury is thought to have been formed in much the same way as the other rocky, terrestrial planets were formed, why is it so laden with iron? There is no plausible fractionation process for the products of the solar nebula that can account for this iron content. Perhaps the most widely (but not universally) accepted explanation is that originally, Mercury was considerably larger than it is today, but that at some point much of the low density mantle and surface rock was blasted away either by large asteroids or through the impact of another small planet.

Mercury has the largest range of hot and cold temperatures in the solar system. Why do you think this is so? Hydrogen, helium, oxygen, sodium, and potassium have been detected in the atmosphere, although the concentration of these materials is very low. There is some evidence of sub-surface ice at both the poles, where temperatures may be as low as 100 Kelvins.

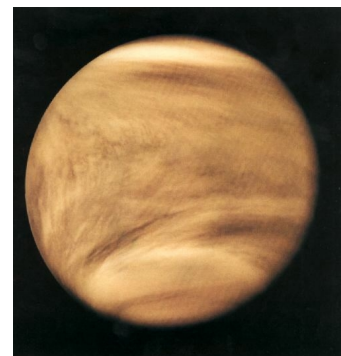
Mercury is indeed a desolate and frightening place that is continuously blasted by the intense radiation of the sun and the solar wind. Nevertheless, over the past few years the importance of Mercury has begun to be realized in the world of planetary science because its surface more closely preserves the ancient history of planet formation than do the surfaces of the other terrestrial planets, which have been modified by recent erosion, volcanic and tectonic activity.

Venus

The second closest planetary relative of the Earth presents a vastly different face to the casual observer than does Mercury. Venus is always totally obscured by clouds and all that the Pioneer Venus spacecraft (1978) ever observed were cloud tops. Nevertheless, various probes dropped through the massive atmosphere have provided information about its composition, temperature, and pressure. And several instruments actually have landed on the surface providing initial tantalizing

glimpses of what the real Venus is like. In 1990 the spacecraft Magellan was placed in orbit around Venus and its radar "eyes" have provided detailed information about the surface topography.

What evolves from the data obtained to date is a picture of a rocky world not greatly different in size from Earth, but with a surface pressure 90 times that of Earth's and a temperature of almost 750 Kelvins. It is indeed a foreboding place. The surface of Venus is covered with myriad volcanoes of all sizes, enormous lava flows, and related, but very unusual structures that have no counterparts on Earth.



While Venus and Earth are of much the same size and composition, their surfaces have rather different histories. The Earth's internal heat emerges as distinct lines of volcanoes located along cracks that divide the planet's surface into several plates. On Venus, where there may indeed be similar plates, the crust is thin and flexible allowing magma to well up and create a plethora of volcanoes—perhaps as many as 100,000 of them. Thinly superimposed on the magma-covered surface are craters left from meteorite impacts. Since there are many fewer impact craters per unit surface area on Venus than on Mercury, it may be concluded that the surface of Venus has undergone more or less continuous renewal from volcanic eruptions that may continue even to this day. In fact the Pioneer Venus craft obtained information in 1978 that suggested there had been a recent injection of sulfur dioxide into the atmosphere. This oxide, which eventually is converted chemically into sulfuric acid, could have arisen from a volcanic eruption. As a result of the extensive volcanism that has afflicted Venus for much of its life, significant concentrations of corrosive sulfuric acid have accumulated in its atmosphere.

Since Venus has an atmosphere, it also has weather, complete with high winds and squalls. This weather, like Earth's, is driven by the energy of the sun, but here the comparison ends because the Venusian clouds are composed mostly of carbon dioxide garnished with sulfuric and hydrofluoric acids, as well as with myriad other molecules. This composition creates a gigantic greenhouse effect that raises the temperature of the surface enormously and makes Venus the hottest planet in the system, even though it is almost twice as far from the sun as is Mercury. At first glance the seemingly large amount of carbon dioxide might be a surprise; however, both carbon and oxygen are common in the universe and Earth's stores of this material are not unlike those of Venus's. On Earth, however, the carbon dioxide is locked up in the form of solid carbonate minerals (limestones) or is dissolved in the oceans instead of floating in the atmosphere.

A more difficult and puzzling problem is the apparent lack of appreciable water on Venus. Clearly liquid water could not exist on the scorching surface, but we might expect to find it in the atmosphere. So far little has been detected. Perhaps the water present long ago was split into its component hydrogen and oxygen molecules by the action of sunlight or through the catalytic reaction with hot surface rocks.

The rotation of Venus about its own axis is of note because Venus rotates more slowly than any other planet (turning once on its axis in 243 Earth days) and it rotates in a backwards sense relative to the rotation of Earth and the other planets. That is to say, the sun appears to rise in the west and set in the east on Venus. The reason for this is the subject of controversy.

This leaves us with the final question of why Venus is so different from Earth. At one time when the sun was younger and less bright, was the surface of Venus a cool, watery swamp having an atmosphere like that of Earth's? Did the increasingly hot sun boil away Venusian liquid water reserves into the atmosphere, creating an ever-increasing greenhouse effect? Did the carbonate rocks then decompose in the intense heat to release carbon dioxide, providing ever more greenhouse heating and the atmosphere as it exists today? Or did Venus never contain appreciable reserves of water? If not, why not? Was some fractionation mechanism at work in the early days that discriminated against the deposition of water on Venus? These and related questions remain unanswered.

Earth

While Earth can claim to be distinctive because it is the largest and most massive of the terrestrial planets, it is the presence of a large satellite, the moon, which clearly distinguishes it from the other planets in this class. Any discussion of Earth must include comments about the moon, and it is important to recognize that reasonably large samples of moon rock have been returned to Earth for study. These rocks proved to contain surprisingly few volatile materials, in particular water. They were bone-dry and different from typical rocks found on the surface of Earth. This suggests, but does not prove, that the moon



was not created under cool conditions, but rather that it was formed as the result of a calamitous collision between a young Earth and a Mars-sized "planet." The incoming object was ripped apart and its remnants were splashed into space as a cloud of hot gases and solid fragments that surrounded the injured Earth. Water from this cloud was lost to outer space and the remaining material condensed to form the moon. The composition of the moon would thus resemble that of the incoming object rather than matching the outer layers of the Earth.

The newly formed moon probably was molten in its earliest stage, but it soon started to cool with the formation of a thin crust of light rock. By 4,000 million years ago the moon had largely solidified without a high density, liquid metal core, but there remained localized hot spots from which lava welled up to fill large

impact basins. This gave rise to the dark plains that are so clearly delineated on the surface. Since then the moon has been struck occasionally by meteoroids, but for all practical purposes it has been devoid of further activity.

The Earth on the other hand has remained alive and geologically active, in part because of its large size. It still stores heat in its interior that originally arose from the collision of the asteroid-sized bodies that coalesced to form the planet and it contains, as well, stores of radioactive elements that are constantly decaying with the release of thermal energy. As a consequence the central core is hot (around 5000 Kelvins). It furthermore is thought to consist largely of solid, highly compressed iron, some of which could have come from the "planet" that collided with the Earth. Surrounding the core is a layer of liquid metallic iron that circulates as a result of the planet's rotation and/or thermal convection currents, giving rise to the strongest magnetic field found among the terrestrial planets. Above the liquid layer and extending to the thin crust is the semi-liquid mantle, consisting of molten rock. This molten rock sometimes breaks through the crust and a volcano is created.

The Earth also is distinguished by the extensive amount of tectonic activity found in the crust, where large plates float and move on the underlying semi-liquid mantle. This tectonic activity coupled with erosion and volcanism has fundamentally altered the surface of the Earth from what it was like during the early days after it was formed.

The erosion of the Earth's surface can be traced in large measure to the presence of copious amounts of liquid water, which again makes this planet unique among the terrestrial set. It also is the case that Earth is the only planet where water is found in three different physical states: gas, liquid, and solid. The origin of the water is not clear, though there is some evidence that water may have come from meteorites. It is clear that the presence of ample amounts of liquid water might be the most important aspect of Earth's character, since life could not have originated and survived without the water.

Finally, Earth is surrounded by a thin veneer of an all-important atmosphere consisting primarily of nitrogen and oxygen. The most outstanding aspect of the atmosphere is the high concentration of oxygen, but one should note as well the low concentration of carbon dioxide relative to that found in other planetary atmospheres. The presence of an atmosphere and magnetosphere, which protect Earth's inhabitants from the constant bombardment of energetic materials and radiation from outer space, also play a vital role in making it possible for Earth to support life.

Mars



The red planet, lying about 50% farther from the sun than the Earth's orbit and containing only a fraction of the Earth's matter. In fact the surface area of Mars is about the same area as the land masses of Earth. Mars is a frozen world where the thin atmosphere consisting of carbon dioxide (95.3%), minor concentrations of N_2 , Ar, and O_2 , and traces of carbon monoxide and water is held in place by a only a small gravitational field. The lack of a substantial atmosphere and the absence of a substantial magnetic field make Mars an easy target for bombardment both by meteorites and by the energetic particles that continuously spew forth from the sun. Should a Martian exist, he or she would have to be a tough customer indeed to have endured conditions at home.

The surface of Mars is scarred in the northern hemisphere with volcanoes. Olympus Mons is the largest found thus far in the solar system. It is pocked with craters in the

southern hemisphere. Also present are canyons and what appear to be riverbeds left over from when this dry planet once had flowing water.

At one point early in its history Mars probably looked like today's Mercury or the Earth's moon—it was covered with impact craters. However, in contrast to Earth, the red planet today probably is extinct, all of its internal energy having been dissipated long ago. Mars is circled by two small satellites, Phobos and Deimos, both of which seem to have a different origin than their host planet.

Long ago convection currents in the hot rocky part of the interior created hot spots that found weak areas in the thick crust and created volcanoes that remained in place for years, building up huge cones and lava deposits. The crust is too thick for tectonic activity with its accompanying volcanism to have occurred. Interestingly, the largest of the volcanoes shows few meteorite impact craters in its flanks, suggesting that it is relatively young on the planetary geological time scale. This suggests a reason for the relatively uncratered northern hemisphere—reasonably late in the planet's history vast deposits of lava covered much of the area, obscuring the original cratered surface.

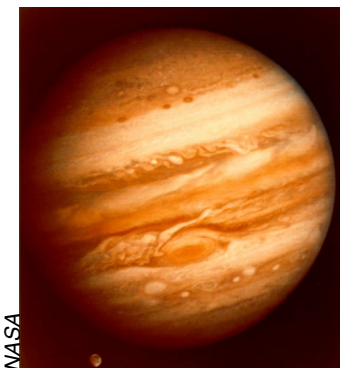
Although thin, the carbon dioxide laden atmosphere gives rise to Martian winds that create immense dust storms and sculpt the surface features of the planet through erosion. The temperature at the pole in winter dips so low that solid carbon dioxide (dry ice) forms and coats the pole with a bright cap, supplementing that provided by the permanent water-ice caps. So much dry ice forms during a Martian winter that the volume of the atmosphere shrinks and the atmospheric pressure varies by as much as 30%.

Viking landers have analyzed the Martian soil, which may generally be characterized as a hydrated iron-rich clay and which gives rise to the characteristic red color of the planet. Interestingly, there were no signs at all of carbon in the soil, ruling out the possibility of finding living matter on Mars, at least in the region sampled by the Viking project.

Questions about the role and presence of water on Mars remain very high on the list of projects for future projects to answer. The deep canyons appear to have been carved by flowing water. Where did the water come from? A reasonable hypothesis is that the volcanism that wracked Mars also laced the atmosphere with water along with carbon dioxide. This created, in turn, a greenhouse effect that raised the temperature of the planet to the point that water could remain liquid. The water then may have precipitated and meandered through the cratered landscape, carving out river valleys and canyons. But what happened to all of the water? Was Mars struck by giant meteorites that resulted in the moist atmosphere being blasted away into space? Or did the solar wind eventually strip away the bulk of the atmosphere, leaving behind little water? Or did the atmosphere thin to the point that the water froze below the surface, where it remains as a permafrost? Answers to these and other questions must await the results of future explorations of this increasingly accessible planet.

THE GIANT PLANETS

Jupiter



The fifth planet from the sun, Jupiter, in a word, is huge. It is by far the largest object in the solar system, with the exception of the sun. All of the other planets could be housed within its volume with room to spare and it is three times more massive than the next heaviest planet. It is blessed with a bevy of moons, some of which are bigger than Mercury and rival Mars in size. These moons are themselves of great interest because of their varied and bizarre characteristics, but they will not be discussed here in any detail. Jupiter also is encircled by a ring of dust, as are the other giant planets.

Jupiter has been observed through terrestrial telescopes for hundreds of years, and sky watchers have been intrigued by the ever-changing patterns of clouds on the planet. However, the landmark that has received the most attention is the Great Red Spot located in the southern hemisphere, which is thought to be a jovian storm three times the size of

Earth that has lasted for centuries.

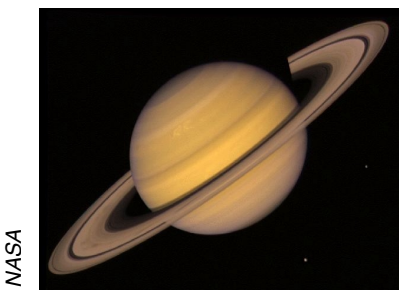
Only the outermost layers of Jupiter are accessible for observation; consequently, its internal structure is largely based on conjecture derived from density and gravity measurements that are bolstered by theoretical modeling. The model that best accounts for most of the observations includes: 1) a rocky/icy core having a mass equivalent to ten or twenty Earth masses,

2) a surrounding layer of metallic hydrogen occupying about two-thirds of the jovian radius, and 3) a convective atmosphere consisting largely of hydrogen and helium. It is interesting that the atmosphere also contains some rather exotic molecules as minor constituents. Such compounds as PH_3 and GeH_4 having been detected experimentally. These exotic materials probably are responsible for tinting the swirling, wind-driven jovian clouds, making them the most colorful in the solar system. Note that Jupiter, like the other giant planets, does not have a surface in the same sense that, say, Mercury does. Jupiter possesses a well-documented, robust magnetic field that conceivably might arise from convective motions within the fluid metallic hydrogen layer just above the core.

Interestingly, Jupiter is generating its own heat, radiating twice as much energy as it receives from the sun. The source of this energy is not certain, but it probably arises from gravitational effects, for example, from the gravitational collapse that occurred when the planet was formed. The internal energy probably does not arise from radioactive decay, as is the case with some of the terrestrial planets.

Even though Jupiter generates some internal heat, it does not mean that it is balmy. The temperature at the top of the atmosphere is estimated to be around 170 Kelvins (approximately -100°Celsius).

Saturn



NASA

Saturn's large, bright, and beautiful rings have long been regarded as one of the most striking and awe-inspiring sights available to the casual stargazer who views the night sky through a small telescope. Pioneer and Voyager spacecrafts have provided even more stunning close-up views of the rings. Clearly Saturn is the crown jewel of the planets that we see in the sky.

Like Jupiter, Saturn is huge. Its mass and volume are about 100 and 750 times those of Earth's, respectively, giving Saturn the lowest density of any planet. The low density immediately suggests, of course, that Saturn, like the other giant planets, consists mainly of gases. These gases principally are hydrogen and helium, although very

minor concentrations of other gases such as ammonia, HCN , and AsH_4 are present as well. The outer layer is depleted in helium.

Saturn also produces energy internally, but the mechanism of energy production is not certain. It does seem clear, however, that the excess internal energy is not the result of gravitational collapse, as is thought to be the case for Jupiter, because Saturn is too small to generate heat through this mechanism. The heat generation may be related to the depletion of helium in the atmosphere, the idea being that the helium atoms deep within the interior are condensing and falling inward, generating heat as they fall. The temperature at the top of the atmosphere is estimated to be a cold 135 Kelvins.

Much of what is often proposed for Saturn's structure is determined through theoretical modeling, because detailed observational data are not available. It is worthy of note that Saturn is flattened more than any other planet. The distance from the center of the planet to the equator is about 12% greater than the distance to the poles. The model currently in vogue includes the following features: 1) A rocky/icy core that extends about 25% of the way to the surface, 2) a zone containing metallic hydrogen that is enriched in helium, and 3) a zone of hydrogen (depleted in helium) that fills the outer 50% of the planet. The structure proposed is not very different from that described above for Jupiter. Saturn also possesses a strong magnetic field, as demonstrated conclusively for the first time by the Pioneer and Voyager missions.

Like Jupiter, Saturn is wracked by terrifically strong winds. In fact, the winds in Saturn's atmosphere are among the most powerful in the solar system, with wind speeds of nearly 2,000 km per hour which are much slower than the solar wind. Although not nearly as evident as the swirls and eddies on Jupiter, Saturn's atmosphere is dotted with comparable features, reflecting what may be similar weather patterns.

Saturn has the most identified satellites in the solar system. While the satellites of other planets are mentioned only in passing, it seems appropriate to focus special attention on Titan, one of Saturn's eighteen or so moons. Titan is larger than the planet Mercury and it has a dense atmosphere—more dense than that of Earth. Furthermore, in distinct contrast to many of the other objects found in the outer reaches of the solar system, it has an atmosphere composed mostly of nitrogen laced with various minor components, including a fascinating variety of hydrocarbons such as ethylene, propane, and

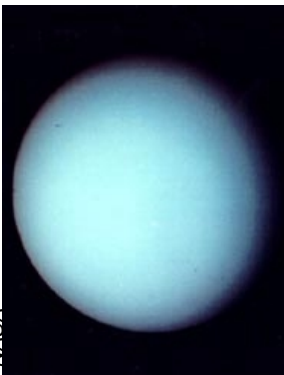
acetylene. Titan is so peculiar and unique that it is regarded as one of the most fascinating solar system bodies for future exploration.

Finally, it would be impossible to end this discussion without further mention of Saturn's famous and beautiful ring system. The features have proven to have a very complex and intriguing structures, consisting of thousands of optically distinct, concentric rings, some of which are circular and others of which are strongly eccentric. The sizes of the particles making up the rings are not well established, but they probably range from micrometers to kilometers in diameter. The chemical composition of the rings is not known, but they seem to be composed of particles covered with a shell of ice. The rings may be constantly replenished with material eroded away from the many moons that "herd" the rings in their orbits. Many important questions remain about the rings, like:

- How did they arise and why is Saturn the only planet having such brilliant and distinctive rings?
- Is it only a matter of timing that has led to this wonderful visual exhibit of planetary diversity?
- Are the rings just debris resulting from a violent collision that shattered one of Saturn's moons, scattering the particles into orbit around Saturn as rings of dust? Did other planets such as Jupiter have similar rings at one time that faded as the particles were swept into the planet by gravitational forces? In a few million years will Saturn's rings similarly become obscure and insignificant?

Future explorations in space will provide answers to these questions.

Uranus



Uranus is a planet that was not known by the ancients. When it was discovered in 1781 by William Herschel, it doubled the size of the known solar system. Uranus is another giant world, but it is so far away that it is not visible to the unaided eye. It perhaps is most notable for the way it is tipped on its side as it orbits around the sun, with the axis of planetary spin pointing almost directly at the sun. It is indeed a mysterious planet, and astronomers have few observational data with which to work at this point. Consequently, models of this planet are even more uncertain than the models of Jupiter and Saturn.

Like the other giant planets, Uranus is thought primarily to contain hydrogen in its outer shell, possibly along with substantial amounts of helium and icy methane. The methane in the outer atmosphere is thought to give rise to the planet's bluish-green tinge. At the "surface" the temperature may hover around 80 Kelvins. One model suggests that the outer shell interfaces with a convective layer around 0.3 of the way to the center of the planet. This layer is characterized as a warm, aqueous, ionic "sea" containing dissolved ammonia and methane, which surrounds a hot rocky core. Of course all this is very speculative at this point and much remains to be learned about this almost featureless planet, on which Voyager found only hints of clouds in the atmosphere along with a very dark, tenuous, and thin ring system. There are at least ten moons orbiting the planet as well.

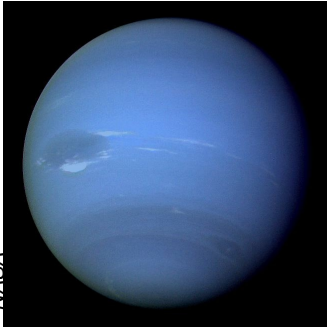
Like Saturn and Jupiter, Uranus possesses a strong magnetic field that is oriented in such a way as to provide a very complex magnetosphere. Unlike Saturn and Jupiter, Uranus does not seem to have an internal source of energy.

Until there are additional deep-space probes that focus on Uranus, this planet is likely to remain as enigmatic and mysterious as it has been since it was first discovered.

Neptune

Neptune is so far away that one must use a telescope to see it at all, even though it is four times larger than Earth. Its existence was first predicted by mathematicians who calculated its position based on the force that it was observed to produce on Uranus as the latter planet moved around in its orbit. Earthbound telescopes reveal Neptune as only a faint blur, and most of what is known was gathered by Voyager 2 in 1989.

Like Uranus, it is necessary to describe Neptune as it has been modeled on the basis of very sketchy observational data. These models suggest that Neptune has a small core of rock/ice surrounded by enormous quantities of water. Layered over the water is an atmosphere consisting mostly of hydrogen and helium gas supplemented with a bit of methane.



Unlike Uranus, Neptune is a net producer of heat energy, emitting about 2.5 times as much energy as it receives from the sun. The mechanism of heat generation is very speculative, but it conceivably could arise from some sort of condensation mechanism like that presumed to exist on Saturn. What heavy material is condensing out? Some have suggested that it is pure carbon—perhaps large chunks of diamond!

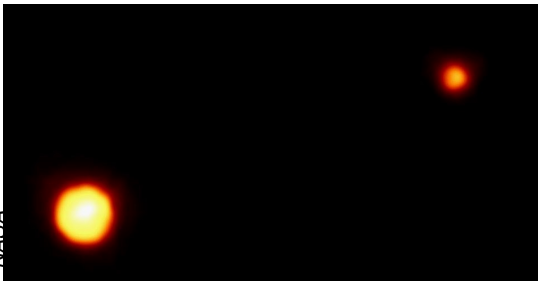
Somewhat surprisingly, Neptune exhibits more surface features than does Uranus. For example, there are dark spots and clouds. And there are tremendous winds, which rage so strongly that they make Neptune the windiest on any of the solar system's planets.

As we might expect, Neptune has rings, but they are very sparse and even Voyager was challenged to observe them. As well, there exists a family of moons. Triton, the largest of

the moons, is indeed unusual in that its geysers of nitrogen gas periodically erupt from the surface. Like the other distant giant planets, much remains to be learned about this fascinating member of the solar system family.

Pluto

Pluto was discovered in 1930 by astronomer Clyde Tombaugh at the Lowell observatory in Flagstaff, Arizona. Should Pluto be regarded as a planet or is it perhaps a very large comet? This is an actively debated topic of contemporary interest. Why? Because Pluto has characteristics quite unlike the other distant planets: it is not large, it is not gaseous, and its orbit around the sun is highly eccentric. It is interesting to note that, although it is usually regarded as the outermost planet, Pluto is actually closer to the sun than Neptune at certain times (for example, from 1979 to 1998) owing to the eccentricity of its orbit.



Pluto has a close neighbor, Charon, which has a radius of about one-half of Pluto's and many now regard the system as a double planet. Their mean density is in the neighborhood of

2 g cm^{-3} . Pluto's surface composition has been determined spectroscopically, with the conclusion that it is covered by methane, carbon monoxide, and nitrogen (the latter being the major component). In contrast the atmosphere of Charon seems not to contain methane. The atmospheric temperatures of these objects are not well known.

In many ways Pluto resembles Triton, the large satellite of Neptune. Yet Pluto orbits the sun, not another planet. Is this sufficient for it to be listed

as the ninth planet of the solar system? One theory suggests that Pluto is an escaped moon of Neptune.

It is important for the reader to recognize that much of what is presented here and elsewhere is based on VERY scanty data, from which astronomers have derived marvelous, and in many cases correct, descriptions of the nature of celestial objects. Yet, opinions often vary as to how to interpret some of these data. In many cases planetary compositions, core descriptions, and so forth are, at best, educated guesses. Please keep in mind that much of what has been written, including this Appendix, is subject to revision as new, more complete information is obtained in the next century.

So the question is, "How does a baseball team compare to the planets?" Well, in both cases there are nine members of the team. But does the resemblance end here? Can the case be made that the diversity on a baseball team compares to that found among the planets? You decide.