2. Giants of Gas and Ice

Immediately beyond the orbit of Mars lies a wide gulf uninhabited by any major planet. It is, however, the abode of a great number of smaller sub-planetary bodies known as "asteroids," about which more shall be said in the following chapter. Further beyond this region, extending to the very edges of the system of major planets, lies the realm of the giant orbs Jupiter, Saturn, Uranus and Neptune. The first two are known as "gas giants" and take us to the limits of the Solar System known to astronomers before the late 1700s. The remaining more modestly proportioned worlds—the "ice giants"—were unknown to the ancients and by comparison with the worlds discussed in the previous chapter of this book are very, *very* far away.

Jupiter

In Greek mythology, Jupiter was the chief of the gods. Not for nothing does the great planet bear this name! It has been said that if an alien were to survey our Solar System, he (she? it?) would probably describe it as a star with one major planet, plus a swarm of minor bodies of little note. Most of the mass of the Sun's system of planets resides in this one massive body and 1,000 orbs the size of Earth could comfortably fit within its globe, but more of this in a moment.

As seen from Earth, Jupiter is regularly the second brightest of the planets. Only Venus consistently surpasses it although very occasionally Mars, at an exceptionally favorable opposition, just manages to outshine it. But Venus is our closest planetary neighbor, so it ought to appear bright! Moreover, it can never be placed opposite the Sun in our skies (the only planet on which that can happen is Mercury) but Jupiter can be visible all night long, the brightest regular nighttime object other than the full Moon that is

D.A.J. Seargent, *Weird Worlds: Bizarre Bodies of the Solar System and Beyond*, Astronomers' Universe, DOI 10.1007/978-1-4614-7064-9_2,
© Springer Science+Business Media New York 2013

capable of this feat. No regular star, other than the Sun itself, is as bright as Jupiter as seen in our skies. (I use the word "regular" here to omit the very occasional transitory object which may indeed outshine Jupiter. The past 1,000 years have seen a couple of supernovae become brighter, but they are hardly "regular" denizens of our skies!)

Unlike Venus however, Jupiter does not shine brightly in our skies because it is very close to Earth. On the contrary, Venus at its nearest is over 18 times closer than Jupiter. Jupiter is bright because it is big—really big. We already mentioned how a hypothetical alien might see this planet's place in the Solar System. Let's look at this in more detail. If we had a large enough pair of scales and placed Jupiter in one pan and all the other planets in the other, Jupiter's pan would crash downwards! The mass of this single giant world is some two and one half times greater than all the other solar worlds combined. In terms of size, the average radius of Jupiter clocks in at almost 44,000 miles or nearly 70,000 km, (yielding a diameter of 88,000 miles or 140,000 km approximately). All the other Solar System bodies—beside the Sun itself—could fit within its volume. (The Sun however, could swallow around 1,000 Jupiters, so remembering this fact helps a little to keep things in perspective!).

Through a telescope, Jupiter is a spectacular sight, second only to Saturn amongst the Sun's planets as a source of wonder and amazement. Though it lacks Saturn's spectacular ring system, its disk appears larger (varying between 29.8 and 50.1 seconds of arc in diameter) due in part to its larger intrinsic size but chiefly because of its greater proximity to Earth. Even a small telescope proves sufficient to show the colored belts of cloud across the planet's disk and a scope of moderate size might also be able to pick out one of the true wonders of this world; the Great Red Spot. This is a cloudy atmospheric eddy large enough to engulf at least two Earths and towering some 5 miles (8 km) above the surrounding cloud deck. This great storm has an amazingly long lifetime. It can certainly be identified with a feature appearing in a drawing of Jupiter made in 1859, became unusually prominent in1878 and is widely held to be identical with a feature noted by G. D. Cassini and independently by R. Hooke in the mid seventeenth century. Over the years it has waxed and waned in

prominence and to a smaller degree in size, and has varied in color from a rather dull grey to conspicuous brick red. A watch on the Spot reveals something else about Jupiter. It is revolving on its axis—and fast! Watching the Spot progress across the visible disk shows that the planet spins on its axis at a remarkable 28,313 miles (45,300 km) per hour, enabling it to make one full turn of its huge bulk in just under 10 h! This rapid rate of rotation shows itself in the relatively conspicuous flattening of the planet's poles. Adding to the telescopic spectacle of Jupiter are the four bright "Galilean" moons—part of the giant planet's vast satellite family—which perform their constant dance around their primary, at some times passing in front of the planet and casting black shadows on the cloud tops, at others passing behind it or disappearing in the giant planet's shadow or even eclipsing one another. These various phenomena are fascinating (especially seeing one of the moons simply fade out as it enters Jupiter's shadow) and certainly add to the visual spectacle of the giant planet. They are also fascinating worlds in their own right, but any further talk of this must wait for a later chapter.

Once, not too many decades ago, Jupiter was pictured as something like an oversized Earth. That is certainly not to say that conditions there were thought to be very Earthlike—far from it—but the realization that the bodies we call "planets" come in such a wide variety of forms did not really come until the advent of space probes. Prior to that, most astronomers assumed almost as a given fact that all planets had the basic structure of our own. That is to say, a planet was a solid body with a hard and well defined surface. There may or may not be an atmosphere, but if one were present, it would exist as a gaseous envelope clearly defined from the surface, much like the familiar air of Earth. Of course, it might be utterly un-Earthlike in composition or density or temperature, but it would at least mimic Earth's in its basic form. Similarly, if a sufficiently dense atmosphere permitted liquid to exist on the surface of a planet, bodies of this liquid would be basically like the oceans and lakes of home. They may not be made of water, but they would still be recognizable as oceans, seas, lakes or just puddles.

With this in mind, Jupiter was pictured as a solid object, having a well defined surface and presumably topographic features such

as mountain ranges and valleys, enveloped in a dense atmosphere filled at high altitude with an abundance of cloud. One model saw it as a rocky world encrusted with layers of ice thousands of miles thick. Other models pictured oceans of liquid ammonia covering much of its surface. The writer recalls one especially vivid description of huge snowflakes of ammonia ice, as large as houses, falling from clouds of the same composition and eventually plunging into what the author described as "that nightmarish ocean" of liquid ammonia. Not a place for a summer holiday to be sure!

Once Jupiter began to be explored by robotic space probes, the picture changed dramatically. From being an oversized and nightmarish Earth, the giant world became something utterly alien. Isaac Asimov was not far wrong when he described Jupiter as a "white hot drop of liquid hydrogen", or words to that effect. Hydrogen is, indeed, the planet's main constituent, comprising around three quarters of the mass of its atmosphere. Helium accounts for a further 24 % with the rest being made up of a variety of substances such as methane, ammonia, hydrogen deuteride, water, ethane, neon and traces of various hydrocarbons such as benzene. Carbon is also present in small amounts, as are ethane, hydrogen sulfide, oxygen, phosphine, sulfur and some silicon-based compounds. The clouds contain a number ices such as frozen ammonia, ammonium hydrosulfide and water.

Imagine descending downward through Jupiter's atmosphere. The first milestone that we pass through is the cloud layer. These are the belts of clouds which give the planet its characteristic appearance in our telescopes and consist chiefly of crystals of ammonia and, maybe, ammonium hydrosulfide. Other materials must be mixed in with these substances as well, as ammonia or ammonium hydrosulfide crystals alone could not produce the colors seen in the cloud belts. It is thought that compounds known as *chromophores* well up from deeper down in the atmosphere and become colorful upon exposure to ultraviolet radiation from the distant Sun. The composition of these chromophores is unknown at present, but phosphorus, sulfur and, possibly, certain hydrocarbons are suspected. The cloud deck is actually very narrow considering the size of the planet and its atmosphere. It appears to be just 30 miles (about 50 km), or thereabouts, thick and to consist of at least two separate layers. The lower, thicker and warmer one

is where the colorful compounds occur. Convections cells rise above this layer and, at their summits, clouds of ammonia crystals waft out into formations not unlike the anvil cirrus of terrestrial thunderstorms, obscuring the colorful underlying layers from our view. Swept along by winds of around 225 miles (360 km) per hour, these spreading "anvil cirrus" form the light-colored *zones* so familiar to observers of the planet. Clear regions between these zones expose the deeper, darker and more colorful clouds known to observers as *belts*. There also seems to be a thin layer of water-ice clouds underneath the ammonia layer and it is here where the famous Jovian lightning plays. Thunderstorms discharging lightning bolts a 1,000 times more powerful than those of Earth have been observed within these water clouds.

As we descend lower and lower into the atmosphere, the air becomes ever more dense and the temperature continues to rise. When we reach a level about 620 miles (1,000 km) below the cloud deck, the mainly-hydrogen atmosphere reaches a so-called supercritical fluid state, i.e. a state in which the distinction between gaseous and liquid phases disappears. For convenience, the "atmosphere" can be considered as liquid below this level, but it must not be thought of as an "ocean" or anything as familiar to we Earthlings as that. There is no actual boundary between the "gas" and the "liquid". One simply passes into the other as the hydrogen grows hotter and denser with increasing depth. Rather arbitrarily, the base of the atmosphere is usually considered to be the level at which pressure reaches ten times that of Earth's sea level; a value reached at a depth of around 3,000 miles (5,000 km) from the outermost fringes of the atmosphere. The density at which the supercritical fluid state is achieved is somewhat higher—about 12 times that of the Earth's atmosphere at sea level.

Descending still further, pressure and temperature continue to climb until, at a level almost 10,000 miles (16,000 km) below the clouds, another transition takes place. At a temperature hotter than the surface of the Sun and a pressure of around 200 GPa, the hydrogen starts to behave as if it were a metal. Through this layer, droplets of helium and neon precipitate downward like a weird kind of rain, effectively reducing their abundance higher in the Jovian atmosphere. Then, right at the center of this unbelievable object, there may (or may not!) be a rocky core of between 12 and

45 Earth masses. Not every planetary scientist agrees that a core formed, while others suggest that even if one did form initially, it may have been wafted away via hot currents of metallic hydrogen and diffused through higher levels of the planet's interior. Hopefully, this question will be answered in the not-too-distant future.

A Ringed Planet

Prior to 1978, Saturn was thought unique (at least in the Solar System) in possessing its spectacular array of rings. But that year, distant Uranus was also found to be encircled by a faint ring system and so it came as no great surprise when, in 1979, images beamed back to Earth from the *Voyager I* space probe disclosed a similar faint system surrounding Jupiter. All four giant planets are today known to possess rings systems, suggesting that these features are probably common adornments of giant worlds throughout the Universe. Saturn's rings are unusual only by being so large and bright. By contrast, the rings of Jupiter are very dim except when imaged by space probes looking back at the planet from a point further from the Sun. If the angle separating the Sun and Jupiter is small, forward scattering of sunlight by the ring particles lights up the ring system, rendering it far more conspicuous than it appears from other perspectives. A homely analogy is the way in which a piece of thistle down drifting high in the air becomes visible as a bright point of light as it passes almost in front of the Sun. From Earth's vantage point of course, Jupiter can never be seen between the observer and the Sun, so its rings can never be enhanced through the forward scattering effect for observers on Earth (just as well actually, as that would mean that Jupiter had migrated to some point sunward of Earth and our world would probably have either been flung out of the Solar System or into the Sun. Missing a good view of the Jovian rings is a small price to pay for avoiding either of these fates!) (Fig. 2.1).

Unlike the rings of Saturn, which are comprised of particles of ice, Jupiter's appear to be mostly made up of dust particles. There are at least three components of the ring system; a main ring which, when compared with the other components, is *relatively* bright, an inner circle known as the halo and an outer gossamer ring. The main ring is thought to be made of dusty material ejected from the

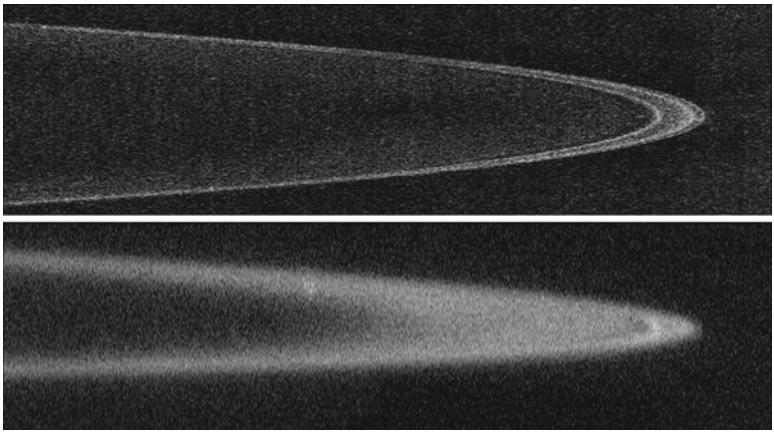


Fig. 2.1 Jupiter's main ring as imaged by *New Horizons* spacecraft (Credit: NASA)

inner moons Adrastea and Metis. Thanks to the powerful gravity of the giant planet, material from these satellites is pulled toward, and thence into orbit around, Jupiter instead of falling back onto the moons themselves. Similarly, material from the moons Thebe and Amalthea probably accounts for the gossamer ring and there is even evidence of a ring of larger, rocky, bodies strung out along the orbit of Amalthea, probably representing debris thrown into space by meteorite impacts on this moon. (Fig. 2.2).

Both the *Galileo* and *New Horizons* spacecraft found something unusual and unexpected about Jupiter's main ring. Within the ring were two sets of spiraling vertical corrugations, one somewhat more prominent than the other. It seems that these were caused by relatively massive objects perturbing the steady state of the ring; the larger of the two resulting from a tilting of the ring out of the equatorial plane by about one and one quarter miles or 2 km. As the spiral patterns were observed to be decaying, the perturbing events must have been very recent. Calculations suggest a date for the formation of the smaller disturbance as sometime during the first 6 months of 1990. The second dated back to 1994. This, we might remember, was the year that a spectacular event—or, rather, series of events—occurred on Jupiter in the form of multiple collisions by a compact group of comets; fragments of the periodic comet Shoemaker-Levy 9 which was tidally disrupted

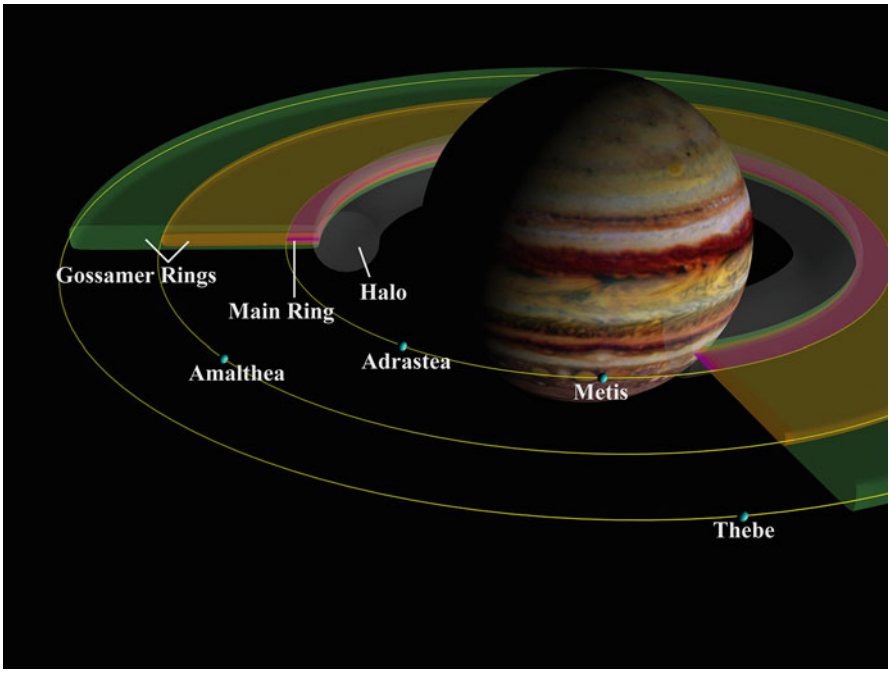


Fig. 2.2 Diagram of Jupiter's ring system (Credit: NASA)

during an extremely close pass of the planet several years earlier. The spiral pattern within the main ring apparently resulted from impact by material from the broken comet. Presumably, the smaller and slightly older spiral pattern resulted from the impact of debris from an earlier comet that was disrupted close to the giant planet. No observations of this hypothesized object are known and there appears to be no evidence of any sizable fragments impacting Jupiter that year, so this was probably a smaller and less active comet that Shoemaker-Levy, albeit one large enough to leave its fading mark on Jupiter's ring.

Jupiter also boasts a "ring" of a different kind; a torus of gas along the orbit of the volcanic moon Io. As we shall see in a Chap. 4, this moon is the most volcanically active place in the Solar System and it is continually belching out material into the space around Jupiter. But Jupiter also possesses a powerful magnetic field; 14 times stronger than that of Earth. Except for transitory sunspots,

Jupiter is the strongest astronomical magnet in the Solar System. Thanks to this powerful planetary magnetosphere, the gases originating from Io are ionized. Sulfur dioxide is broken down into sulfur and oxygen ions and, mixing with hydrogen ions from Jupiter's own outer atmosphere, form a plasma sheet oriented with the equatorial plane of the planet. Other substances as well boil out from Io and into the plasma sheet, although the origin of all of them is not entirely clear. The yellow-orange glow of sodium was recognized quite early and potassium and chlorine have also been detected. The presence of both chlorine and sodium apparently betrays the presence of sodium chloride (table salt) on Io.

The Jovian plasma sheet is responsible for the intense bursts of radio waves once thought to be due to tremendously powerful flashes of lightning on Jupiter. There *is* lightning on the planet, and it *is* powerful, but it is not responsible for these strong radio emissions. The real reason for these bursts is even more interesting. As Io crosses Jupiter's lines of magnetic field, an electric current as high as two *trillion* watts flows down the lines and into the polar regions of Jupiter. Radio waves are generated through a cyclotron maser mechanism and beamed outward in cones of intense radio emission. In a sense, Jupiter acts as a very weak radio pulsar! When the Earth passes through one of these cones, the blast of radio waves received makes Jupiter appear as a more intense beacon than the Sun itself.

Possessing such a powerful magnetic field, it comes as no surprise to learn that Jupiter also displays spectacular aurora, intensified even further in regions where the magnetic flux tubes connecting Io, and to a lesser degree the other large moons, impinge upon its atmosphere.

About 75 times the distance of Jupiter's radius (approximately 3,000 miles or 5,000 km, in round figures) from the planet, the Jovian magnetosphere interacts with the solar wind, giving rise to a bow shock and elongating "down wind" almost as far as the orbit of Saturn. This makes the length of the "magnetotail" more than 80 % as great as the Jupiter/Sun distance—albeit in the opposite direction! The magnetic field is tilted about 10° with respect to Jupiter's axis of rotation.

The Amazing Shrinking Planet

Jupiter gives out more heat than it receives from the Sun. In effect, it "shines" very faintly in infrared light. Given this fact plus the further knowledge that the overwhelming portion of its mass is in the form of hydrogen and helium, some science writers have described it as being "almost a star" or even "a failed star". True, its composition more closely resembles stars like the Sun than planets like Earth or Mars (its composition is not *exactly* that of the Sun—there is less neon, not quite as much helium and somewhat more of the heavier inert gases—but the overall composition is still pretty close to the Sun's). Yet, its accretion from a protoplanetary disk is not the way stars are thought to form and the fact remains that it does *not* shine in our skies as a second Sun. One astronomer quipped that calling Jupiter "almost a star" is like calling him "almost a millionaire". He is "almost" there in the sense that he earns enough money to live but (being a scientist and not a sports champion or film star) his income still falls far short of the millionaire status!

It is calculated that the material at the core of Jupiter is around six times hotter than the photosphere of the Sun and experiences a pressure of somewhere between 3,000 and 4,500 GPa. This heat is generated, not by thermonuclear fusion as in a star, but by the steady contraction of the planet. Yes, Jupiter is shrinking; at a rate of approximately 2 cm (not quite an inch) each year. It's loss of girth is not going to be noticed anytime soon, but looking backward in time indicates that in its youth the planet had a diameter about twice that of today.

Curiously, if more mass were to be added to Jupiter, it would not become any larger in diameter. On the contrary, there would be little change in physical size until it increased to about 1.6 times its actual mass, after which its present size would be *less*, not greater! To the profound jealousy of dieting humans, the more Jupiter "eats" the "thinner" it becomes! This seeming paradox is the result of the increasing density and compression of matter in the planet's core and it is thought that the present diameter of Jupiter is about as large as a planet of its composition, age and general evolutionary history can become. Younger gas giants can be larger (we have already said that Jupiter itself had a more obese

youth) and planets which could be called "bloated Jupiters" have been discovered in orbit around other stars—in orbits very close to the star itself where heating is extreme—but for a planet having Jupiter's age and position, it is about as wide as it can be and it can only slim down further with the passing years.

Adding mass to the planet and thereby further compressing its interior will, however, raise its internal temperature and it is here where the "almost a star" exaggeration is born. If a dozen extra planets of Jupiter's mass were crammed into its volume—so that its mass was increased to 13 times its actual value—temperature and pressure conditions deep within its core would become great enough for fusion of deuterium (the "heavy" isotope of hydrogen) to take place and Jupiter would become a brown dwarf; one of those transition objects between planets and full-blown stars. These could almost be called "missing links" between planets and stars except that, happily, they are no longer missing. They are objects that have thermonuclear fusion, albeit of a comparatively feeble form, at their core in the manner of a star, and dust particles and gaseous methane in their atmospheres in the manner of gas giant planets.

If Jupiter's mass further increased by around 65 times, lithium would also start to fuse in its core. It would still be a brown dwarf, just a heavier and somewhat more active variety. But imagine that Jupiter continues swallowing clones of itself until its total mass reached 75 times its present value. At that point, conditions at the core become extreme enough for hydrogen to fuse into helium and a true star is born. Only then would Jupiter become a genuine star; one of those small, faint, relatively cool but extremely long-lived and very common luminaries known as red dwarfs. So if "nearly" means one seventy-fifth of the mass of the smallest genuine stars, then the great planet could indeed be said to be "nearly a star". In truth though, a factor of 75 is not all that close. Jupiter, for all its "stellar" similarities, remains a true planet, albeit one that from Earth's point of view is really weird in its general characteristics. It is a world without a surface, where the atmosphere and the body of the planet merge without clear distinction, where as much heat comes from the interior depths as from the distant Sun and where giant cyclonic storms that could swallow the Earth and still have room to spare rage unabated for hundreds or maybe even thousands

of years. Atmospheric circulation and upwelling convective clouds are therefore driven more by the characteristics of the planet itself (internal heat, rapid rotation) than by solar heating and we can imagine that even if Jupiter were flung into interstellar space, the tremendous thunderstorms and cyclones that churn through its atmosphere would continue unchecked—unlike the Earth where all air would freeze onto a barren surface.

We shall visit the Jupiter system again in Chap. 4 when we look at its extensive family of moons, especially the "big four" Galilean moons visible from Earth in even the smallest of backyard telescopes. But for the present, let's move on to the next of the Sun's gas giants, the magnificent ringed world, Saturn and see what weirdness might also await us there.

Saturn

The sixth planet out from the Sun, the spectacular Saturn, is in many respects a scaled-down version of Jupiter. It is, however, considerably less massive, weighing in at a little over 95 Earth masses. This is quite lightweight compared with Jupiter which, as we saw, comes in just shy of 318 Earth masses. Yet, the discrepancy in the volume of the two giants is a good deal less pronounced. Jupiter could swallow over a 1,000 Earths (1,321.3 to be precise) but Saturn could contain almost 764. This conspicuous difference in mass and considerably less divergence in volume means that Saturn is a planet of very low density. Indeed, of all the worlds in the Solar System, it is the least dense and—at a shade under 0.69 g/cm^3, is the only one having a mean density less than that of water. Hence the oft-quoted statement that, were there an ocean large enough to accommodate it, Saturn would float. (Nevertheless, we will see in the final chapter that it no longer holds the record for the least dense known planet, although we need to leave the Solar System to find those that beat it). The equatorial diameter of Saturn is some 75,335 miles (120,536 km) or nearly 9.5 times that of Earth.

Like the Solar System's largest member, Saturn is primarily composed of hydrogen (about 96 % of its atmosphere) with most of the rest being helium (approximately 3 %) plus traces of methane, ammonia, hydrogen deuteride and very tiny traces of ethane, acetylene, propane and phosphine. As is true of Jupiter,

this mainly-hydrogen atmosphere becomes denser with depth, transitioning through a liquid phase of helium-saturated molecular hydrogen and eventually becoming metallic. There are no atmosphere/ocean/solid surface boundaries; no hard and fast dividing line between the various phases. Evidence has been found for a small rocky core (estimated to be between 9 and 22 times the mass of Earth—"small" in comparison to the size of the entire planet), but as is the case with Jupiter, this is not certain. Whatever the truth about a core, the temperature at the center of the planet is very high, albeit not so extreme as Jupiter. Temperatures are estimated to reach a level almost twice that of the Sun's photosphere and (again very reminiscent of Jupiter) heat propagates through the planet such that Saturn actually radiates away into space 2.5 times the energy that it receives from the Sun. The source of this amount of heat is really something of a mystery. Jupiter, we recall, generates its internal heat through a slow and steady shrinkage leading to increasing compression deep within. Saturn is also slowly shrinking and compressing, but that process does not appear capable on its own of supplying the degree of heating that has been observed. It must be getting help from somewhere; some other process that is presumably not active on Jupiter or else is of very minor importance there. An interesting suggestion involves the generation of heat through the friction of helium "rain drops" passing through the deep hydrogen atmosphere on their way toward the planet's center. We saw that helium "rain" is also thought to occur deep within Jupiter, but there is reason to think that Saturn has "rained out" more of its atmospheric helium than its bigger brother. The outer layers of its atmosphere appear seriously depleted in this gas by comparison with the solar abundance and even with the content of Jupiter's outer atmosphere. A continuous helium "rain" could explain both this atmospheric depletion of the gas and the unusually high degree of heat being generated deep down in the bowels of the planet. As to the destination of all this helium—where it finally ends up—a suggestion has been made that it accumulates into a helium shell surrounding the planet's core—if, indeed, such a core exists.

When viewed through our telescopes, the disk of Saturn appears rather bland by comparison with that of Jupiter. Latitudinal markings are faint and except for the rare appearance of a "Great White Spot" (more about these a little later) spots and other

definite markings are pale and infrequent. Nothing resembling the persistent Great Red Spot of Jupiter is found on Saturn. It is easy to assume that this blander profile compared with Jupiter implies a quieter and more sedate world and, indeed, that is just how astronomers of an earlier generation interpreted it. But such an interpretation turns out to be quite wrong. As has happened so often since the advent of space probes, in situ imaging has overturned many of our earlier ideas about the other members of the Solar System acquired through years of ground based telescopic observation. Saturn is anything but a quiet and peaceful planet. Quite the opposite. Winds reaching a staggering 1,116 miles (1,800 km) per hour howl through its clouds and thunderstorms unlike anything seen on Earth or even on Jupiter flash and crash within the atmosphere. The calm appearance in our telescopes is a false impression caused by a high haze of ammonia ice crystals that largely block from view the turmoil going on beneath. Lower cloud decks appear to be mostly comprised of ammonium hydrosulfide ice, water ice and at lower altitudes, droplets of liquid water in which ammonia is dissolved. Hydrocarbon chemical reactions also take place in the higher atmosphere triggered by the action of solar ultraviolet light on the small amounts of atmospheric methane present. The products of these reactions are carried downward into the deeper atmosphere in a kind of photochemical cycle that is apparently modified by the planet's seasonal cycle.

Allusion has already been made to the occurrence of gigantic thunderstorms on Saturn. Strangely, these seem to be confined to a narrow "storm ally" at 35° southern latitude. Whether this is a fixed feature on the planet or whether the latitude varies with the season is not known at present. Having a year equivalent to around 30 of ours, the seasons on Saturn are necessarily slow and our close monitoring has not continued long enough to tease out the various seasonal effects that might be present. In any case, the storms might be confined to a particular region of the planet, but they make up for their localized nature with exceptional size, endurance and ferocity. One particular example was followed by the *Cassini* spacecraft from November 2007 until July 2008 and another from January until October of 2009. The diameter of this latter storm was almost 86 % that of the Moon; a colossal 1,850 miles or 3,000 km! The lightning that it sparked was

equally impressive, each flash carrying a power equivalent to 10,000 terrestrial lightning bolts. On the other hand, it appears that Saturn sports just one thunderstorm at a time, unlike Earth whose thunderstorms, though tiny by Saturnian standards, number between 6,000 and 8,000 at any given moment. A peculiarity about the thunderheads of Saturn is that they seem to come in two colors. The ones noted thus far have either been very bright or very dark. It seems that Saturn's thunderstorms brook no shades of grey! Clouds of the first variety are thought to acquire their luster from crystals of ammonia ice, maybe in the form of high spreading sheets of cirrus analogous to the anvils that cap terrestrial thunderstorms in their decaying phase. The dark clouds are believed to be rich in carbon, presumably deposited from carbonaceous compounds built up through the action of lightning.

A curious recurring type of feature already touched on in passing is the phenomenon of the Great White Spots. These massive atmospheric disturbances are the most conspicuous features seen on the disk of Saturn through terrestrial telescopes, but they are not permanent features akin to the Great Red Spot of Jupiter. There is no persistent "Spot" on Saturn, but the GWS outbreaks seem to be relatively regular occurrences around the time of summer solstice in Saturn's northern hemisphere. Given the length of the planet's year, that means that they occur about every 30 Earth years and have been noted in 1876, 1933, 1969 and, more recently, in 1990 and 2010. There should have been one in the early 1900s but either it did not happen for some reason or it passed unseen. Maybe it occurred but was not as conspicuous as usual. In any case, a reoccurrence of the phenomenon is again due sometime in the 2030s or 2040s, so (young readers please take note!) a careful watch of the planet then might prove interesting. Considering that Saturn appears quite a deal smaller in our telescopes than Jupiter, these Spots are comparatively more striking than that planet's famous blemish. The one in 1876, for example, was observed with a 2.4-in. (6-cm) telescope and that of 1933 was followed by a very young Patrick Moore using a 3-in. (7.5-cm) telescope. The 1990 example eventually extended into a white band encircling the entire planet.

When the most recent eruption occurred—late in 2010—*Cassini* was in place for a close-up view of the process. From the probe's observation of radio bursts and upwelling of warm gas from deeper atmospheric levels, scientists conclude that

this "Spot" (and presumably its earlier counterparts) was triggered by a gigantic thunderstorm deep within the layer of water clouds. This storm burst upward through the visible cloud layers in a way similar to—though on a vastly grander scale—the "overshooting" clouds of powerful supercell storms on Earth; the type which bring devastating weather in the form of large hail and powerful tornadoes. We can hardly imagine what these Saturnain supercounterparts must be like!

Actually, the 2010 storm came some 10 years earlier than had been predicted from the average rate of such events. Following the 1990 "Spot", there had been expectations that another would occur around the year 2020, so the appearance of the most recent one came as something of a surprise. Which only goes to show that predicting storms on other planets is no easier than forecasting them here on Earth!

Even weirder examples of extraterrestrial meteorology are to be found at the poles of Saturn. Infrared images of the planet's south pole reveal a "warm" polar vortex unlike anything else seen in the Solar System. In strong contrast to Earth and Mars, the south pole of Saturn appears to be the warmest place on the planet (excluding the planetary interior of course) with temperatures around 63 °C higher than the planetary average. This is still a shivering –122 °C however, so it is not exactly "warm" by our standards!

Something even less expected exists at the Saturnian north pole; a persisting hexagon! This pattern of cloud extends to about 78° north, appears to rotate at the same velocity as the interior of the planet (almost 10.67 h) and, unlike other clouds, does not shift in longitude. Exactly what causes it is something of a mystery, although most planetary scientists think that it is a standing atmospheric wave pattern of some kind. It has even been suggested that it might be an odd sort of auroral phenomenon, although this seems unlikely.

As expected for a planet basically similar to Jupiter, Saturn also possesses a magnetic field, however its strength in no way approaches that of the king of planets. In fact, it even falls a little short of Earth's at just one twentieth the value of Jupiter's. Nevertheless, the magnetosphere of the planet ensures the occurrence of aurora around Saturn's poles and is known to extend out beyond its giant moon Titan. As we shall see in a later chapter, this moon

boasts a very significant atmosphere and ions from the outer fringes of this are wafted off into the magnetosphere, contributing to the plasma trapped there.

The magnetic field is also responsible for sending out radio emissions having a remarkably regular period. These were observed by the *Voyager* flybys in the early 1980s and their period associated with that of the planet's rotation; the rotating orb effectively carries the magnetic field around with it. But as the *Cassini* space probe approached the planet in 2004, new measurements of its period of rotation showed a marked discrepancy from the earlier results. As measured by the radio emissions, the planet's rotation period had increased by more than 5 min since the early 1980s! Further measurements 3 years later confirmed this. Something appeared to be holding back the rotation of the magnetic field. But what could have this effect? How could the magnetic field of a planet be retarded in this way?

The culprit is believed to be another of Saturn's moons—Enceladus. As we shall see in due course, this small moon is best known for its geyser-like ice volcanoes. Water vapor erupted by this object is thought to become electrified and exert such a large drag upon the magnetic field of the planet as to measurably retard its rotational velocity. Strange as it may seem, this tiny moon cheekily tugs at the magnetic coat of its majestic primary!

Planet of Rings

So far, we have mentioned only in passing the one feature for which the planet Saturn is best known; the feature that comes to the mind of astronomer and layperson alike as soon as the planet's name is mentioned. We refer of course, to the magnificent system of rings which gird it (Fig. 2.3).

Long thought unique in the Solar System, the first indication of their existence came as long ago as 1610 when Galileo noted that something looked decidedly odd about the shape of the planet as seen through his tiny refracting telescope. Saturn appeared to have handles—or something that at least looked like handles! Hardly expecting a planet to have handles and innocent of the phenomenon of planetary rings, the pioneer telescopic astronomer opted for the existence of twin moons, one on each side of the planet at very small distances from it. It was not until 1655 that Christian

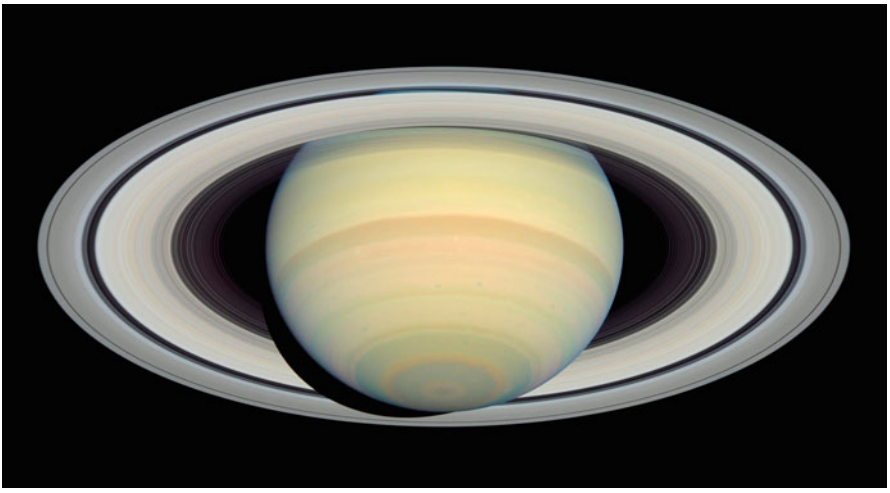


Fig. 2.3 Saturn and its spectacular ring system (Credit: NASA)

Huygens fully discerned the rings through a larger and more powerful telescope than Galileo's.

Curiously however, there are mysterious hints in the ancient legends of diverse cultures suggesting a prior knowledge of the planet's rings. Many of these (such as the bands around the feet of the statue of the god Saturn at the Roman Capitol) are most probably simple coincidences, but what can we say about an ancient engraved wooden panel from Mexico depicting what appears to be the family of planets, one of which is encircled by a ring (reproduced in Kingsboroughs's *Antiquities of Mexico*, 1830)? And what of the claim that the Maori of New Zealand had knowledge of the ringed planet? E. Best writes in *The Astronomical Knowledge of the Maori, Genuine and Empirical* (1922),

> PAREARAU represents one of the planets. Stowell says that it is Saturn; that Parearau is a descriptive name for the planet, and describes its appearance, surrounded by a ring. The word pare denotes a fillet or headband; arau means "entangled" – or perhaps "Surrounded" in this case, if the natives really can see the pare of Saturn with the naked eye. If so, then the name seems a suitable one.

Best goes on to say that a Maori, commenting on the origin of the name, said that the planet is called Parearau because "her band quite surrounds her." That sounds like the description of an encircling ring but, of course, it is notoriously easy to read all manner

of things back into old legends and stories from other cultures. Nevertheless, the apparently widespread allusions to Saturn being "bound" or "surrounded" is curious to say the least.

Project 1: The Visibility of Saturn's Rings

It is well known that Saturn's rings are clearly visible in very small telescopes. A 2.5-in. refractor is enough to give a spectacular view and even large binoculars will show them clearly enough to distinguish their nature. We wonder if, had Galileo somehow known in advance that the planet was surrounded by a ring system, would he have recognized the true nature of what he was seeing in his tiny instrument and stopped thinking in terms of close moons and the like.

How small can an instrument be and still discern the rings? The issue is one of magnification more than aperture as a 2-in. telescope is sufficient with moderate magnifications. But can you detect the rings using 10×50 binoculars (which have the same aperture)? Or 7×50 binoculars? What is the smallest instrument through which you can see the rings?

Leaving aside ancient tales and returning to our present state of knowledge, we know that the diameter of the main ring system has a width of 71,294 miles (114,070 km), from about 4,134 miles (6,630 km) above the planet's equator out to around 75,430 miles or 120,700 km. Yet, despite this considerable width, the rings average only about 65 ft (20 m) in thickness. This makes them, by comparison, thinner than a sheet of tissue paper. They are neither solid nor gaseous, but can be interpreted as a vast system of millions upon millions of tiny micro-moons, ranging in size from around 30 ft (10 m or thereabouts) all the way down to mere specks of dust. The composition of these particles/bodies is principally water ice (accounting for some 93 % of ring material) with the remainder being amorphous carbon and very slight traces of more or less complex organic compounds of the type known as tholins. Beyond the principle or, as we might say, "classical" ring system lies a very faint and distant oddity of a ring tilted at an angle of 27° to the main system and comprised of bodies that orbit



Fig. 2.4 An eclipse of the Sun by Saturn as imaged by *Cassini* spacecraft, 15 September 2006 (Credit: NASA)

Saturn in the opposite direction to those of the nearer and better behaved rings. This black sheep in the Saturnian family appears to be associated with the backward-orbiting (i.e. retrograde) satellite Phoebe; a small and dark body that has also been found guilty of darkening one hemisphere of another of Saturn's moons, Iapetus. Apparently, Phoebe has shed quite a lot of dark dust over the years, not only supplying another ring to the already well endowed planet but also coating the hemisphere of neighboring Iapetus that this moon keeps turned toward it. We will say more about the two-faced Iapetus and the dust-shedding Phoebe in Chap. 4 (Fig. 2.4).

It was earlier thought that the main ring system was primordial; left over from material that failed to be incorporated into the building of the planet billions of years ago. More recent thinking understands the rings to be a lot younger—more like several hundreds of millions of years old—and sees them as consisting of fragments of a disrupted satellite. There is certainly enough material in the ring system to construct a small moon if it all snowballed together. Estimates of the ring system's total mass range from 3×10^{19} to 9×10^{19} kg. One suggestion involves a large moon plunging into the planet and being stripped of its icy shell just before the fatal crash. Be that as it may, some of the ring particles are thought to be of even more recent parentage, namely icy particles ejected by the ice volcanoes of the small but active moon Enceladus, about which more will be said in Chap. 4.

In the smallest of telescopes, the system looks like a single bright ring, but in reality it is rather more complicated than that. It is actually a complex of many rings, separated by divisions and gaps, some of which are visible in quite small telescopes and others revealed only close at hand from space probes. The spaces between rings are not totally void although the particle density there is far lower than within the bright rings themselves. The most conspicuous of the divisions is known as Cassini's division in honor of its discoverer, G. Cassini, who found it in 1675. It is some 3,000 miles (4,800 km) wide and is visible in all but the very smallest telescopes. Indeed, the telescope with which Cassini discovered it had a lens aperture of just 2.5 in. (about 6-cm.) about equal to those incongruously white-tube refractors that became the first telescopes of so many young amateur astronomers of the present writer's generation. The second most prominent is known as Encke's gap and may be detected in telescopes of 8 in. (20-cm) or larger. Despite its official name, it was not discovered by Encke, but by J. F. Keeler in 1888, some 23 years after Encke's death. Encke had contributed so much to the study of the ring system however, that giving his name to this rather prominent ring feature was felt to be right and proper. Lest we are tempted to feel sorry for Keeler, it should be mentioned that his name was also given to a ring gap; one about a tenth the width of Encke's. (As an aside, Encke's Comet—which we shall mention later in this book—was likewise discovered by other people, but was given Encke's name in recognition of his computational work concerning its orbit; work which enabled this object to be re-observed at later returns to the Sun). Encke's gap is located some 83,494 miles (133,590 km) from Saturn's center and is home to the small satellite Pan. This moon appears to have swept the region along its orbit relatively clean of ring material thereby carving out this gap in the rings. The gap is not totally free of material however as the *Cassini* space probe discovered at least three thin knotted ringlets lying within it. On either side of the gap, spiral density waves have been noted. It is thought that these are induced by resonances with other moons orbiting nearby, albeit somewhat further out, than Pan. Pan does, however, induce its own set of spiraling wakes.

Although Cassini's division and Encke's gap are the most prominent divisions in the ring system, space missions—in

particular *Voyager*—have identified literally thousands of narrow gaps and thin ringlets within the overall system. Some of these arise from the clearing of ring material by moonlets, such as the clearing of Encke's gap by Pan. Others arise from the sort of resonance between orbiting particles and more distant moons that exist between asteroids of the Main Belt and Jupiter and which create the so-called Kirkwood Gaps within the asteroid system that we shall meet in Chap. 3. Where the orbital periods of ring particles are such that these particles repeatedly come into conjunction at the same places in their orbits, with one of the more distant moons, their orbital eccentricity will be pumped up until they are ejected from these regions altogether. In this way, the regions of resonance are cleared of material. The chief region cleared by this means is the Cassini division. Less severe resonances between ring particles and inner moons create spiral waves through the periodic gravitational perturbations of these moons. Other gentle waves passing through the rings appear to be density waves; small-scale counterparts of the galactic waves that give spiral galaxies their spectacular arms.

In the case of narrow rings, their constituent particles are herded together by the combined action of two "shepherd moons" or satellites located just beyond each edge of the ring. A prime example of this is a very thin outer feature known as the F ring, "shepherded" by the two small moons Prometheus and Pandora (Fig. 2.5).

Speaking of small moons, it should be mentioned that tiny satellites lurk within the rings themselves although only the mere tip of this particular iceberg has been discovered as yet. The A ring, especially, is thought to host moons galore. In 2006, 4 tiny ones were found by the *Cassini* craft. The moons themselves were too small to be imaged directly; what was found were "propeller-shaped" disturbances of the ring particles making distinctive patterns within the ring itself. These patterns were several miles across, but the moons themselves were estimated as being only about 320 ft (100 m) or so in diameter. The following year, a further eight moons were found by the same method and the next year added 150 more. It is estimated that some 3,000 inhabit a zone within the ring about 81,000 miles (130,000 km) out from the center of the planet.

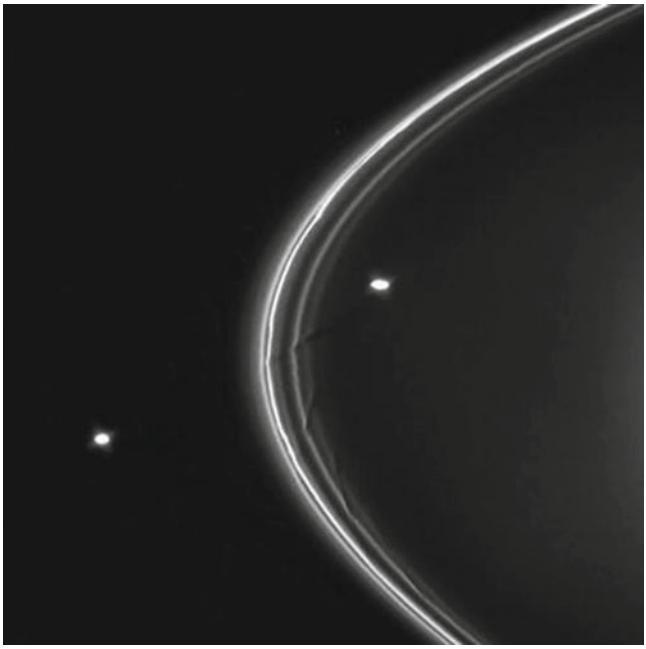


Fig. 2.5 F ring and its shepherd moons, Prometheus (*inside ring*) and Pandora (*outside ring*) as imaged by *Cassini* (Credit: NASA)

There is also evidence of a multitude of moonlets orbiting within the F ring. Odd-looking features that have been given the name of "jets" have been observed within this ring. These come in a wide range of sizes. Large jets stretching for hundreds of miles have been imaged and are believed to arise from small moons colliding with the ring. In 2004, a small moon (designated S2004/S6) was found near the F ring and appears to be pursuing an orbit that periodically makes a passage through the ring. This moon is probably typical of the bodies causing the larger jets. However, in addition to these features, some 570 micro-jets have been noted by the *Cassini* spacecraft up to early 2012. These extend for only a few tens of miles and decay after several hours or, at most, days. Fortunately though, one such micro-jet was serendipitously caught in action while *Cassini* was imaging the shepherd moon Prometheus. This jet extended outward for some 31 miles (50 km) before falling back toward the ring. The distance from the jet's tip to the F ring's core was measured at just under 17 miles or 27 km. Small, briefly existing, jets of this variety are thought to be the

results of impacts by very small and icy moonlets (around 0.6 miles or 1 km in diameter) on the F ring. The particular example imaged by *Cassini* is thought to have been caused by one of these moonlets hitting the ring at a very low velocity, indicative of something orbiting close to the ring itself and not coming in from further afield on a more eccentric orbit and higher velocity. According to Nick Attree of Queen Mary University of London, some of these impacting moonlets might be destroyed by their encounters with the rings, presumably bequeathing their icy remains to the F ring in the form of fresh ring particles.

Another surprising finding from data beamed back by the *Cassini* probe is that the rings have an atmosphere! This is not simply an outer fringe of the planetary atmosphere, but a tenuous gaseous envelope surrounding the ring system itself and consisting of molecular oxygen and presumably molecular hydrogen, both derived from the action of ultraviolet radiation on the ring particles which, we recall, are mostly comprised of water ice. It hardly needs comment that this atmosphere is very, very, thin. Indeed, it has been estimated that if was completely condensed out evenly across the ring system, it would form a layer scarcely one atom thick! Although this atmosphere was discovered at close range by a space probe, the *Hubble Space Telescope* has also detected an equally sparse envelope of the hydroxyl radical (OH). Also a dissociation product of water, this does not originate from the ring particles but from molecules of water ejected into space by the ice volcanoes of Enceladus and broken down by the bombardment of energetic ions in Saturn's near environment.

Of Spokes and Spirals

From afar, the rings of Saturn appear calm and stately. Yet, close views from space probes show that changes of various types do occur on timescales of just years. An example of these changes is the evolution of one of three very faint ringlets within the planet's D ring; the dim innermost ring of the system. These three ringlets were discovered in *Voyager 1* images procured in 1980. But when the *Cassini* probe imaged them in 2005, the middle one had not only grown broader but had actually migrated some 125 miles (200 km) inward toward the planet.

Broadening and migrating ringlets were not the only changes having taken place between *Voyager* and *Cassini*. When the first of these spacecraft arrived at Saturn in 1980, a strange and totally unexpected ring feature was noted; one that to this day has eluded a comprehensive explanation. The rings were crossed by radial streaks suitably dubbed *spokes* by the *Voyage*r team. These presented a problem in so far as they were remarkably persistent in a way that features resulting from straightforward orbital mechanics should not be. They simply defied an explanation in mechanical terms. A clue to the nature of the material comprising them was given by the way in which they reflected incident sunlight. In *backscattered* light (at small phase angles, more or less opposite the Sun) the spokes stood out *dark* against the bright background of the rings. However, the converse was true at larger phase angles, where Saturn was more of less between the Sun and Voyager. Looking back at the planet, the spokes were imaged as standing out *brightly* against what had become the less intense background of the rings. The changeover from darker-than-the-background to brighter-than-the-background occurred at phase angles of around 60°. At larger phase angles, *forward scattering* of sunlight caused the spokes to significantly brighten, just as the same forward scattering phenomenon causes drifting spider's web and thistledown to light up when it passes more or less in front of the Sun in a clear sky. Now, particles forward scatter light in different ways and to differing degrees depending upon their size, general nature, and composition. Fine sand does it differently to poppy seeds for example. So by analyzing how the material in the spokes looked at differing phase angles, scientists determined that these features were made up of very fine—microscopic in fact—dust particles suspended above the main disk of the ring system. Moreover, the motion of the spokes was found to be essentially in sync with the rotation of Saturn's magnetosphere. These two findings left but one satisfactory conclusion; the particles within the spokes were experiencing electrostatic suspension! But just why that should be and exactly how and why these suspended particles should align into the observed spokes was not clear then … and it is still not clear today. Some planetary scientists suspect a connection with the incredible thunderstorms that rage in the planet's storm ally, while

others think that micrometeoroid impacts on the ring particles might be responsible, but no mechanism is clearly obvious.

As if to complicate matters still further, when the *Cassini* probe began its imaging of Saturn in 2004, not a spoke was to be seen. Then, on 5 September 2005, they reappeared and have become more prominent since then. This suggests that the spokes are a seasonal phenomenon, absent for much of the planet's long year and appearing around the time of the equinoxes. If that is correct, this pattern is obviously telling us something, although precisely *what* remains obscure.

Equally interesting but (we believe!) not quite as mysterious as the spokes are a series of finescale structures found in the D ring. First detected in the gap between the C ring and part of the D, these consist of a series of waves separated by a space of just under 19 miles (about 30 km) but extending a distance of almost 12,000 miles (19,000 km) to the inner edge of the B ring. They appear to be part of a system of vertical corrugations of between about 6.5 and 65 ft (2–20 m) amplitude arranged in a spiral pattern. Interestingly, the period of these waves was found to be decreasing and this allowed scientists to deduce that the pattern itself had its birth sometime in late 1983. We recall that two very similar patterns were found in Jupiter's main ring and one of these appeared to be associated with the Comet Shoemaker-Levy 9 event of 1994. The Saturn ring spiral is thought to have been similarly caused by the impact of a debris cloud having a mass of around 10^{12} kg.; the debris of a small disrupted comet that passed very close to Saturn and was torn to pieces by the ringed planet's tidal effects late in 1983. Like the 1990 Jupiter event, no direct impact evidence is known, but at Saturn's distance any observational evidence of a comet or its impact, even assuming that any sizable portion did actually reach the planet, is not surprising.

Saturn is without doubt a planet of wonder. Here is a giant world that could float on water were there an ocean large enough to accommodate it; a world of incredible winds and enormous thunderstorms, of spectacular rings and myriad moons of all sizes; from the planet scale of giant Titan to the mini-moons tucked inside the propeller-shaped disturbances of the A ring. Some of the

moons of Saturn are as strange and mysterious as the planet itself. One has ice volcanoes, another may have its own ring system, one has an atmosphere denser than Earth's, methane rainstorms, seas and rivers of liquid hydrocarbons, and two are seriously considered as possible homes of alien life. We shall return to the Saturn system in Chaps. 4 and 5 and take a closer look at these moons but for now the seventh of the Sun's major planets awaits us. Let's see what weirdness is found lurking there too!

Uranus

With Saturn, we arrive at the limit of the planetary system known to the ancients. Yet, from time to time, a keen-sighted early astronomer may well have spied a small star-like point of light that did not keep to one place amongst the constellations. But if anybody did see it in ancient times, it was apparently not recognized for what it truly was; an extra "wandering star". It was simply too faint and slow moving to betray its true nature.

Coming to more modern times, there is no doubt that observations of the planet were made without its true nature having been recognized. The earliest of which we have knowledge was back in 1690 when John Flamsteed, Britain's first Astronomer Royal, found it but mistook it for a star, actually charting it as 34 Tauri. It seems that Flamsteed observed it at least six times but apparently did not discern its slow motion with respect to nearby field stars. Later, Pierre Lemonnier in France made at least 12 observations between 1750 and 1769. During one sequence of observation, he even saw it on four consecutive nights, yet its motion was too slow for him to recognize. It was not until March 13, 1781 that its true nature began to be suspected. On that night William Herschel found an unknown object that he initially mistook for a comet but which subsequent observations by himself and other astronomers eventually proved to be an additional Solar System planet. Herschel was using a telescope when he found the planet, but it is not difficult to see with the naked eye under clear and dark skies and, on occasions when it traverses a familiar pattern of faint stars, is "discoverable" with the naked eye.

Compared with the long known planets, Uranus is, however, a faint object. But that shyness has nothing to do with its size. Its equatorial diameter of around 31,949 miles (51,118 km) it is just over four times that of Earth. This makes it a pretty big globe, albeit significantly smaller than either Jupiter or Saturn. The real reason for its comparative faintness is its great distance from Sun and Earth. It orbits the Sun at an average distance of around 1,797,924,428 miles (2,876,679,084 km) or about twice that of Saturn. At that distance, the planet takes just over 84.3 Earth years to complete a single trip around the Sun.

In broad terms, Uranus is more akin to Jupiter and Saturn than it is to Earth or Mars and older astronomy books almost inevitably lump the big four—Jupiter, Saturn Uranus and Neptune—together either as "gas giants" or simply as "giants". This is essentially correct, although in more recent times astronomers have been prone to distinguishing between the first two giant planets and these more modest giants, distinguishing the latter as "ice giants". This term should not, however, mislead us into picturing these worlds simply as great balls of frozen volatiles. Like Jupiter and Saturn, Uranus has a deep atmosphere comprised mostly of hydrogen (83 %) and helium (15 %) with around 2.3 % of methane and a trace of hydrogen deuteride. It also contains ice crystals of water, ammonia, ammonium hydrosulfide and methane in its atmosphere, but the "ice" within the body of the planet is, as we shall soon see, not at all like the stuff we find outside on a frosty morning (Fig. 2.6).

The mass of Uranus is approximately 14.5 times that of Earth, making it the least massive of the four giant planets and with a diameter about four times that of our planet, it is the second least dense member of the Sun's planetary retinue, although at 1.27 times the density of water it would, unlike Saturn, sink if dropped into some vast cosmic ocean.

Although there remains some uncertainty as to the precise nature of this planet, what may be called the standard model pictures Uranus as consisting of three layers, namely, a small core of about 0.55 Earth masses and comprised of rocky material, a mantle accounting for 13.4 Earth masses or thereabouts and consisting of a hot and dense fluid composed of water, ammonia and other volatiles grading without definite boundary into a gaseous outer

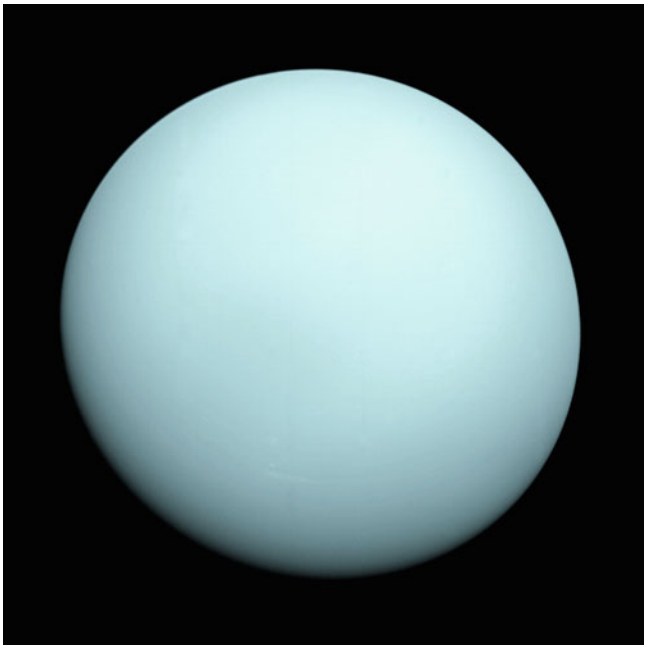


Fig. 2.6 The bland disk of Uranus (Credit: NASA)

region (an "atmosphere"), principally of hydrogen and helium and having a total mass approximately half that of Earth. The mantle has variously been referred to as an ice mantle or as a water-ammonia ocean, but neither of these terms is used in the same sense as they are in familiar conversation. A hot and dense fluid is not what we think of when we hear the word "ice". By the same token, "ocean" also conjures up equally inappropriate images. On Earth, for example, ocean, land and atmosphere are clearly defined, but no such readily discernible borders exist on Uranus. At some level, the fluid simply reaches a sufficiently low density to be deemed an atmosphere or, from the other direction, the "atmosphere" simply thickens into something more like a liquid than a gas.

This atmosphere is subdivided further into the troposphere where pressures decrease from 300 times that of Earth's atmosphere at sea level to just one tenth of Earth's sea level pressure and temperatures fall from about 320 K in the lower regions to between 49 and 57 K at the highest reaches. The value of 49 K is

the lowest recorded not just on Uranus but on any planet in the Solar System. The atmospheric level marked by this temperature defines the tropopause or the boundary at which the troposphere gives way to the stratosphere. The latter exists outward to around 2,500 miles (4,000 km). At that distance, atmospheric pressure is just 0.0000000001 that at sea level on Earth and the stratosphere gives way to the thermosphere or corona; a *very* tenuous mantle of gas, unlike anything associated with other Solar System planets, that extends out as far as 31,250 miles (50,000 km) from the planet's nominal surface. This "surface", by the way, is not a true physical feature of the planet but (in common with the other giants) simply a convenient convention where atmospheric pressure is equal to that of sea level on Earth. It lies within the troposphere, around 187.5 miles (300 km) from that layer's "base" and just over 31 miles (50 km) below the tropopause.

Like its terrestrial counterpart, the troposphere of Uranus is an active region of the planet's atmosphere. Although the disk of the planet does not show the wealth of features displayed by Jupiter or even Saturn, the tropospheric zone is nevertheless marked by complex structures of cloud. It is thought that several cloudy layers exist within this portion of the atmosphere. At levels where the pressure is between 50 and 100 times that of terrestrial sea level, water clouds are believed to occur. Above them, in the 20–40 pressure range, a layer of ammonium hydrosulfide clouds is hypothesized and at still higher levels (in 3–10 pressure range) hydrogen sulfide or ammonia clouds are found. Beyond these again, at levels where pressure has dropped to between one and two times that of Earth's sea level, thin methane clouds have been detected.

For a planet that rotates swiftly (17 h 14 min for the interior of Uranus) we would expect strong winds. We would not be disappointed! Indeed, at latitudes of approximately 60° south, clouds have been seen whipping right around the planet in just 14 h; faster than its rotation. Powerful winds, with velocities as high as 560 miles (900 km) per hour have also been monitored at around 50° latitude in the northern hemisphere. A strange feature of the wind pattern, as determined by tracking tropospheric clouds, is that the more gentle equatorial winds do *not* follow the direction of the planet's rotation. They blow backwards, so to speak! The velocities of these equatorial winds range from 112 to 225 miles

(180–360 km) per hour—not really "gentle" but still a good deal less than those of higher latitudes. The strongest near-equatorial winds blow at latitudes of approximately 20° where, interestingly and perhaps significantly, the lowest tropospheric temperatures have also been recorded. Beyond this latitude, winds change direction and blow with the planet's rotation, increasing in velocity until they peak near 60°. At even higher latitude, velocities fall off again, dropping to essentially calm at the poles themselves.

Conditions within the troposphere (which we might describe as the weather conditions of the planet) appear to have altered since our first really good close-up look through the eyes of *Voyager* in 1986. In some respects, these first detailed views of Uranus were disappointing. Uranus looked very bland; not at all dynamic like the two larger giant planets. Not that it was entirely without detail. A narrow band or "collar" of cloud was observed at latitudes of –45 to –50 and thought to be a denser region of the high layer methane cloud sheet. A bright cloud formation—presumably of the same type—also formed a cap over the southern polar region and some dark bands were evident near the equator. No major "spots" or cyclonic storms were active however, just ten small bright clouds, mostly a few degrees north of the edge of the collar cloud. The planet's northern hemisphere could not be observed during the *Voyager* flyby.

By the beginning of the present century, the far northern region of the planet was beginning to come into view from the Earth's perspective and observations made with the *Hubble Space Telescope* and the Keck reflector initially revealed a very asymmetric planet. The clouds near the south pole were bright, but they had no counterparts near the north. Southern Uranus was bright and northern Uranus dark! But that was about to change. By 2007, following the equinox of the long Uranian year, the southern collar almost vanished while a faint ring of cloud began to take shape around +45°—a northern collar was forming!

Not only that, but in recent years clouds are increasing in number and spots are beginning to appear. Increased numbers of clouds were already being found during the 1990s as new high resolution imaging enabled more careful study of the planet from Earth and as the planet's northern hemisphere came increasingly into view. Most of these early discovered clouds were in the northern

hemisphere and it was thought at the time that this imbalance between hemispheres was probably due to the bright collar cloud of the southern hemisphere obscuring any similar features forming there. In consequence, as more of the darker "collarless" northern hemisphere became visible, astronomers had a better chance of finding clouds in that region. Continuing observation proved that this was not the case. The increase in cloud numbers was real, although the clouds in one hemisphere differed from those of the other. Northern clouds appeared sharper and brighter than their southern counterparts and they apparently formed at greater altitudes. Many of the clouds were short-lived (some persisting for just a few hours) although one is suspected of being identical with a feature observed by *Voyager* back in 1986. If that is true, it would appear that some may persist for years, decades or maybe even longer. As mentioned, spots (storms) have started showing up as well in recent years. The first of these—the Uranus Dark Spot as it has been called—was found in 2006 and imaged by the *Hubble Space Telescope*. Two years prior to this, a persistent thunderstorm was noted. Uranus seems to be waking up after presenting its sleepy face to *Voyager* back in 1986. Moreover, activity seems to be moving from the southern to the northern hemisphere as the planet moves away from its solstice of the 1990s. (It should be mentioned that the hemispheres of Uranus experience extended periods of daylight and darkness because of a peculiarity in the planet's axial tilt. But more about that in a little while.)

Beyond the active troposphere, the quieter stratosphere is a region of rising temperatures, from the very cold tropopause to around 850 K at the base of the thermosphere. The heating of the stratospheric layer principally results from the absorption of ultraviolet and infrared light from the Sun by atmospheric hydrocarbon compounds such as methane, ethane and acetylene, although some heat is also conducted downward from the thermosphere. The hydrocarbons themselves are principally confined to a layer between about 62 and 187 miles (100–300 km) altitude with ethane and acetylene tending to condense into a haze layer rather low in the stratosphere. It is likely that this haze is responsible for the somewhat bland face of Uranus, not unlike the erroneous "quiet" impression given to Saturn by that planet's high altitude haze of ammonia ice crystals.

The stratosphere eventually gives way to the thermosphere/corona, a vast but tenuous envelope having a relatively uniform temperature of around 800–850 K. The source of heat for this region remains a mystery. The Sun is simply too far away for its radiation to account for this degree of heating. Neither does auroral activity appear adequate for the task. (Indeed, although auroras do occur on Uranus, activity is much more subdued than on either Jupiter or Saturn). This outermost envelope of the planetary atmosphere consists mainly of hydrogen, but in addition to molecular hydrogen, there are also many free hydrogen atoms that waft off into an extended corona out to the distance of one diameter of the planet from its nominal surface. This feature is, as previously noted, a unique characteristic of Uranus and is a consequence both of the low mass of hydrogen atoms and of the high temperature of the thermosphere. An explanation awaits a full understanding of the reason for this heating. The corona extends so far from the planet that it causes a certain depletion of the ring system (see below) by exerting drag on the small particles orbiting there.

In addition to these atmospheric layers, Uranus also sports an ionosphere extending between 1,250 and 6,250 miles (2,000–10,000 km). Notice that, at these altitudes, the ionosphere overlaps part of the stratosphere as well as the thermosphere. It is actually denser than the corresponding ionospheres of either Saturn or Neptune, possibly due to the concentration of hydrocarbons at stratospheric levels. Its density fluctuates with solar activity, indicating that it is being sustained by the ultraviolet radiation of the distant Sun.

The Reclining Planet!

One of the weirdest things about Uranus is the tilt of its axis of rotation. Unlike the other major planets whose axes of rotation show modest departure from the perpendicular, that of Uranus tilts to almost 98°, so that instead of "standing" in its orbit, this planet "reclines" on its side. Another way of expressing this is to say that the planet's axis of rotation is almost parallel to the plane of the Solar System, but however it is expressed, the situation is certainly very strange and unique amongst the major bodies of the Sun's family (Pluto, as we shall later see, shares a similar reclining attitude, but this world is no longer considered a major

member of the Sun's family!). Around the time of the solstice, one of the planet's poles faces the Sun while the other is deep in darkness. At the following solstice, the dark and daylight poles are reversed. Because of the length of the Uranian year (about 84 Earth years) each pole receives around 42 years of daylight followed by 42 years of darkness. What we might think of as a normal day/night sequence is only experienced, at these times, by a narrow strip near the equator and even here the Sun remains very low over the horizon. Around the times of equinox however, the equatorial regions face the Sun and "normal" day/night cycles are experienced over a wider region of the planet. One result of the axial tilt is a greater solar energy input, on average over the period of a Uranian year, at the poles than at the equator. Yet, paradoxically, the equatorial regions are warmer. The reason for this is not known.

The tilt is not just a characteristic of the planet itself. The entire Uranian system of satellites and rings (more about these shortly!) also shares it. Because the satellites and rings orbit the planet at low inclination to its equator their orbits are, consequently, close to perpendicular to the planetary plane. The entire system is seriously askew!

Why does this planet have such an extreme axial tilt? Patrick Moore joked that, according to an old legend, Earth's axis had once been upright but was made to tilt because of the sins of humanity. What must have happened on Uranus? Moore asked! Old tales notwithstanding, a more likely explanation involves a collision between the planet and an Earth-sized body very early in the life of the Solar System. Some astronomers think that this scenario might also explain another Uranian curiosity. Unlike the other giant planets, Uranus radiates very little internal heat (just 1.1 times as much as it receives from the Sun). The reason for this anomaly is not immediately obvious, although some sort of internal barrier to heat deep within has been suggested. Alternatively, the core temperature may have been depleted and most of its primordial heat expelled when the planet was struck by the same giant impactor that literally knocked it on its side.

Curiously, although the rotational axis of Uranus is so strongly tilted, its magnetic field is not. Prior to the *Voyager* encounter in 1986, astronomers assumed that the magnetic field would more or less align with the rotational axis and that the Uranian magnetic

poles would also lie very close to the ecliptic plane. That appeared a very reasonable conclusion based on observations of the other planets and the assumption that Uranus behaved as the other planets in this respect.

Reasonable indeed, but totally wrong! Not only is the magnetic field tilted 59° from the planet's rotational axis, but the field is not even centered on the planet's core. The center of the field is displaced from the planetary center by almost one third of the planet's radius in the direction of the south pole! One result of this is a highly lopsided magnetosphere with the magnetic field strength at the "surface" being stronger in the northern than in the southern hemisphere. A further result is the occurrence of aurora far from the high latitude regions. Because of the "sideway's" rotation of Uranus, its extended magnetosphere (magnetotail) is twisted like a corkscrew as it extends away from the planet in the anti-solar direction. Protons and electrons, together with a small number of H_2^+ ions, probably emerging (at least in part) from the extended corona become trapped in the magnetic field and continually pepper the moons and ring particles, probably contributing to the dark color of the latter via a relatively rapid pace of space weathering.

Although the oddly tilted magnetic field seemed initially to be a strange departure from the other planets, this peculiarity was later found to be shared by the other "ice giant", Neptune and may well be a common feature of worlds of this type. It has been suggested that, whereas the field of planets as diverse as Earth and Jupiter originate within the core of these worlds, those of the ice giants might be generated within the water/ammonia "ocean" or at some depth not far below the nominal surface. For the present however, these off-center fields continue to be mysterious.

Another Ringed Planet!

The discoverer of Uranus, William Herschel, maintained that this planet possessed rings similar to those of Saturn. He claimed to have detected the ring in 1789, describing it as red in color and even deduced its angle relative to Earth. Unfortunately, because Herschel's ring system was never confirmed and never acquired wide acceptance amongst astronomers, the rings of Uranus were by and large forgotten (Fig. 2.7).

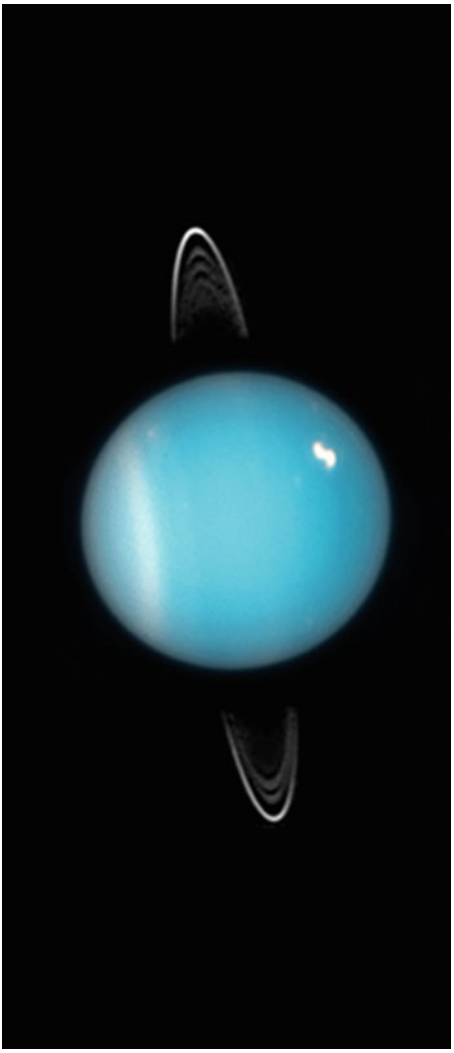


Fig. 2.7 Uranus, showing atmospheric clouds and rings (Credit: NASA)

This all changed in 1977. On March 10 of that year, Uranus was predicted to occult (eclipse) a star catalogued as SAO 158687 and a team of scientists—James Elliot, Edward Dunham and Douglas Mink—planned to take full advantage of this opportunity by observing the occultation from the Kuiper Airborne Observatory. Needless to say, they were not seeking planetary rings, but occultations of stars provide good opportunities to study a planet's atmosphere as the light of the star briefly shines through the

gaseous envelop before being eclipsed by the opaque disk and briefly acts as a probe of the outer regions of the atmospheric mantle. Moreover, because star positions are known with a high degree of accuracy, very accurately timed occultations enable precise positions of the occulting body to be determined. Upon analyzing its results, the team found that the star had unexpectedly vanished for a brief time just before the expected occultation began. One of the scientists quipped that it must have passed behind the ring. A true word spoken in jest as it turned out. Further examination revealed that the star had blinked out five times both before and after the occultation. The first suspicion that a new satellite had been discovered was quickly dismissed. All joking aside, the team really *had* discovered a Uranian ring system! Additional rings were later detected and the system eventually imaged by *Voyager* in 1986. The space craft also discovered an additional two rings, increasing the total to 11.

The ring system surrounds the planet's equator and shares its unusual tilt, as we earlier remarked. The rings are optically faint, in part because the particles comprising them are grey in color, possibly (as mentioned above) due to space weathering by charged particles within the planet's magnetosphere. The particles are also quite large (perhaps "bodies" rather than "particles" would be a better word to describe most of them), the majority ranging in size from about 8 in. to some 65 ft (20 cm to 20 m), with very little fine dust to reflect incident sunlight. The rings are actually quite opaque, a fact aiding their 1977 discovery. The main ring system extends from about 24,000 to 61,000 miles (38,000–98,000 km) from the planet, although each of the separate rings is individually only a few miles wide. This narrowness is a little odd and seems to imply the existence of "shepherd moons" constraining the spread of the debris that forms the rings. However, suitable shepherds have only been found for the fifth ring from the planet, in the forms of the small moons Cordelia and Ophelia. Similar moons are believed to exist for the others as well, but have thus far eluded discovery. If the other shepherds continue to be elusive however, it may be back to the drawing board for an explanation of the small width of the rings (Fig. 2.7).

The ring system is thought to be quite young by the standards of such things, probably only about 600 million years old and to

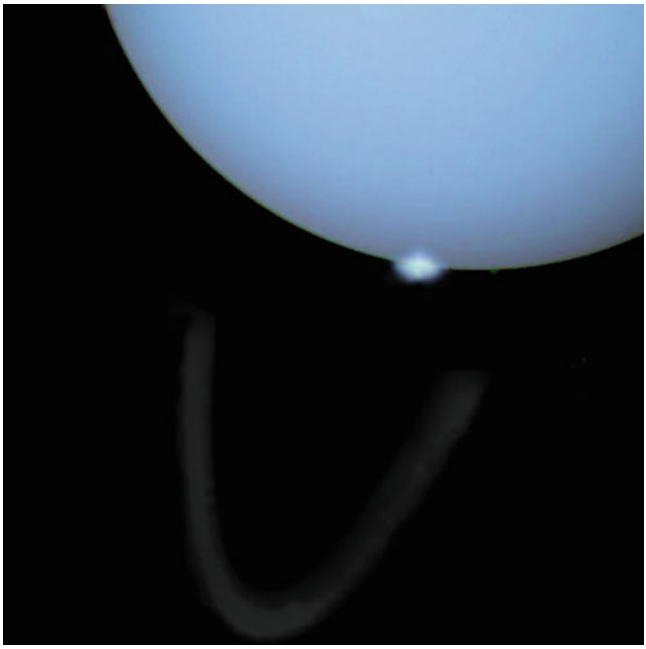


Fig. 2.8 Uranus, rings and auroral activity (Credit: NASA)

represent the remains of two or more moons that once orbited in this region before coming to grief in a destructive collision.

Far from the planet, at over twice the distance of the main ring system, a pair of rings forming an "outer" system was discovered by the *Hubble Space Telescope* in 2005, bringing the total number to 13. The *Hubble Telescope* also found two small moons sharing the orbit of the outermost ring. Unlike the inner rings, these distant ones are not drab grey in color. The innermost is red and the outermost blue, according to observations made in April 2006 at the Keck Observatory. It is thought that the outermost (blue) ring might be composed of minute particles of water ice originating on the surface of one of the satellites (now known as Mab) discovered in 2005. If small enough, ice particles can scatter blue light giving a ring of suitable particles the required color (Fig. 2.8).

Does the discovery of a ring system finally vindicate Herschel's observations? Not really. The brightness, color and even the orientation of his reported rings do not square with the ones found in recent years. Presumably, Herschel was deceived by reflections within the telescope or some such phenomenon and simply read too much into too little. He was not the first to do that, nor was

he the last. It is one of the perpetual hazards of visual astronomy. A little like the Martian canals … although in this instance, Herschel was closer to the mark. Uranus at least *does* have rings, even if not the ones he thought he saw!

Neptune

Being accustomed to drawings or models of the Solar System in which the major planets are represented by globes sitting astride neat concentric rings around the yellow disk or globe doubling as the Sun, we are apt to (subconsciously) think of it as a relatively compact family of worlds were neighbors orbit quite close together. But diagrams and models are deceptive at this point. Not deliberately of course, but inevitably. If the Solar System were drawn to scale or a scale model made for display purposes, either the orbits of the inner planets would be too small to see or the display would become too large to be practical. The truth is, the Solar System is a very big place!

The planet Uranus, as we have just seen, orbits the Sun at a distance of close to 1.8 *billion* miles. That is over 19 times the distance from Earth to Sun. But beyond Uranus, there is a gap of just over another billion miles before the next planet, Neptune, is reached. The average distance of this remote world is some 30 times larger than the space between Earth and Sun (Fig. 2.9).

Neptune differs from the other major planets of the Solar System in being the only one that is not visible with the naked eye (although a good pair of opera glasses will show it) as well as being the only one whose discovery was not a matter of accident. At least, in so far as its "official" discovery is concerned because, like Uranus, observations of the planet were made before its true nature was realized. It appears in two of Galileo's drawings made on December 28, 1612 and January 27, 1613. Galileo's principal subject of the drawings was Jupiter, but one of the background "stars" that he depicted has since been identified as Neptune. It just happened to be close to Jupiter in the sky at that time. Oddly, it appears that he was aware of a slight movement in one of these "stars" between his drawings, but apparently did not follow this up any further. Galileo's other astronomical discoveries caused

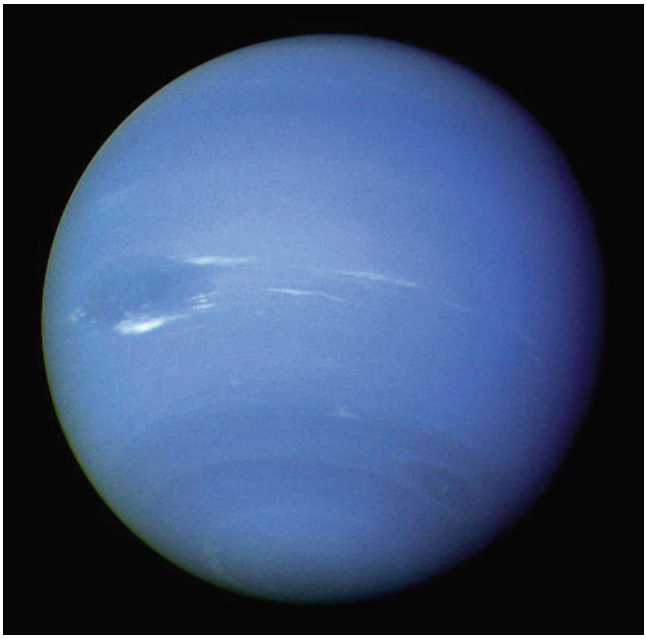


Fig. 2.9 Neptune, showing signs of atmospheric activity as imaged by Voyager 2, 16–17 August, 1989 (Credit: NASA)

a big enough stir amongst the intellectuals of his day, so maybe finding another planet would have been too much to take in—but it would be interesting to know how the history of astronomy may have developed had Neptune been recognized before Uranus!

Real astronomical history, of course, took another and possibly even more interesting turn. To briefly reiterate the well known story, Alexis Bouvard noticed, following his 1821 publication of the orbit of Uranus, that this planet was not behaving quite as he had predicted. Continuing observations revealed that Uranus was drifting slightly from its predicted path and this led Bouvard to hypothesize that another planetary body must be gravitationally perturbing its orbit. Working from this hypothesis, John Couch Adams made several calculations—between the years 1843 and 1846—of the possible path of the proposed new planet. Working independently, Urbain Le Verrier also made several calculations during the years 1845 and 1846 and when these were published, Adams managed to persuade a seemingly skeptical James Challis, director of Cambridge Observatory, to conduct a search for

the planet. This search apparently proved fruitless, but in the meantime—across the English Channel—Le Verrier successfully persuaded Johann Gottfried Galle of the Berlin Observatory to conduct a search of his own. One of Galle's students, Heinrich d'Arrest made the suggestion to Galle that a recently drawn star chart of the requisite region of sky should be examined in the hope of finding a "star" that did not remain at a fixed position. This procedure paid quick dividends, as that very night (September 23, 1846) the planet was found by the Galle/d'Arrest team just 1° from the Le Verrier and 12° from the Adams predicted positions. Back in England, Challis belatedly realized that he had actually observed the planet on August 8 and again on August 12 without realizing it. His lack of an up-to-date chart, and (dare we suggest it?) his apparent lack of enthusiasm for the project cost him the recognition for an important discovery in planetary science.

Just 17 days after the "official" discovery of Neptune, the planet's largest moon (Triton) was found by William Lassell, but the planet is so faint and distant that no obvious detail could be discerned on the disk itself. Prior to the advent of space probes, space-based telescopes and adaptive optics, little could be learned about Neptune and it was generally assumed that it was a slightly smaller and more remote twin of Uranus (and there was not a great deal known about *that* planet either!). That was quite a reasonable assumption and, broadly speaking, it is true enough. Nevertheless, Neptune differs from Uranus in some important respects and, like every planet examined thus far, is very much its own person.

The planet resembles Uranus in so far as both are classified as "ice giants", using "ice" in the rather extended manner that we have already spoken about when Uranus was discussed. In common with Uranus, Neptune has a deep atmosphere estimated to contain between 5 % and 10 % of the planet's total mass and to extend, possibly, as much as 10 % or 20 % of the distance inward toward the presumed planetary core. At high altitudes, this gaseous envelop consists of 80 % hydrogen, 19 % helium and some methane. This last gas absorbs red light and its presence in approximately equal quantities in the atmospheres of both Uranus and Neptune plays an important role in giving these worlds their blue coloration. The color of Neptune is, however, more pronounced than the pale icy blue of Uranus, possibly indicating that something in addition to methane is responsible for its color.

Project 2: Colors of the Ice Giants

Images beamed back from space probes and from the *Hubble Space Telescope* clearly reveal the ice giants to be, like Earth though for very different reasons, "pale blue dots"—indeed, not altogether that "pale" in the case of Neptune! Yet, in many books on observational astronomy, we see these planets being described as appearing *green* in optical telescopes. Patrick Moore speaks of the "dim greenish disc" of Uranus as seen in small telescopes and one handbook of observational astronomy describes Uranus as "a tiny green object" and Neptune as having a "faint greenish color" as seen in modest instruments. Some publications have even referred to these worlds as the "green giants". Why *green*? Why not *blue*? ("Bluish-grey" or "grayish-blue" have been about the closest to Neptune's real color that this writer can recall seeing published in the literature of visual planet observing).

Our atmosphere is not as transparent to the shorter wavelengths of light. This is a good thing in so far as it protects us from dangerous short-wave ultraviolet and harder radiation, but it also depletes the blue light from astronomical sources. The Sun is a good example. To us, observing from the bottom of Earth's ocean of air, the Sun appears yellow. Yet, from outer space, it shines with a bluish-white radiance. Here on the ground, fluorescent lamps marked as 6,000 K shine a light which is clearly a little on the blue side of pure white, yet 6,000 K is also approximately the temperature of the Sun's photosphere. Take a 6,000 K lamp hundreds of miles above the Earth's surface and view it through a telescope, and it would also appear yellow—just like the Sun and other G-type stars. Now, returning to the ice giants, their atmospheres absorb the longer wavelengths (red light) thanks to the presence of methane and whatever else it is in Neptune's atmosphere that adds to the absorption of these wavelengths. The light reflected back from these planets is therefore bluer than incident sunlight, hence their color. However, as this light passes through Earth's atmosphere, blue wavelengths are absorbed

Continued

Project 2: (continued)

more than light of longer wavelengths and the perceived color of these planets is—in a manner of speaking—reddened; just as the Sun is "reddened" from blue-white to a shade of yellow. But because the light reflected from these planets is bluer than direct sunlight, the "reddening" does not go as far down the spectrum as yellow. It stops one color short—at green.

What color do they appear to you? Do you see much difference in their respective colors? (In comparing their colors, remember that Uranus is about five times brighter than Neptune. We cannot detect color in faint objects, which is why neither planet looks very colorful in, say, a pair of small binoculars. Neptune appears in a 12-in. telescope about as bright as Uranus does in a 6-in., so color comparisons made with the same instrument may be less reliable than when a larger aperture is used for Neptune.) Do the colors alter appreciably when the planets are observed at lower elevations?

As Uranus is a paler blue than Neptune, we may expect it to appear more of a yellowish-green while Neptune is a more definitive green. Is that true or incorrect in your experience?

At deeper levels, this gaseous component merges (as is typical with giant planets, without any well defined boundary) with a mantle of "ices" in the atypical sense of the word used in planetary science; that is to say, with a hot, highly dense fluid of water, methane and ammonia existing at temperatures between 2,000 and 5,000 K. The total mass of this mantle is estimated to be some 10–15 times that of the entire planet Earth. It has been theorized that at a depth of nearly 4,400 miles (about 7,000 km) methane decomposes into carbon and hydrogen. Thanks to the prevailing high pressure and temperature, the carbon component is thought to take the form of crystals of diamond, which then fall toward the core as continuous diamond sleet. Other weird processes are hypothesized to occur within the mantle as well. It has been hypothesized that there may be a layer of ionic water in which the water molecules are broken down into a soup of ionized oxygen and hydrogen atoms. Still deeper in the mantle, there may even

be a region of "superionic water" where oxygen crystallizes and hydrogen ions float around freely within this crystal lattice of oxygen!

Also in common with Uranus, Neptune is believed to have an iron-nickel-silicate core thought to be about 1.2 times as massive as the Earth. The pressure at the center of this core—the very center of the planet itself—is estimated to be about seven million times greater than that of Earth's atmosphere at sea level and to possess a temperature possibly as high as 5,400 K.

The magnetic field of Neptune also has close resemblances to that of its nearest neighbor. Just as the Uranian field is tilted with respect to the rotational axis of that planet, so the Neptunian field is likewise tilted—to some 47° relative to its rotational axis and well offset (by some 8,438 miles or 15,500 km) from the planet's center. This discovery, made by the *Voyager 2* probe, came as a surprise to planetary scientists. The strange arrangement of the Uranian field was already known but was assumed to be a consequence of the extreme axial tilt of that planet. The strong similarity between the Uranian and Neptunian magnetospheres was not expected and has caused scientists to rethink their hypotheses as to how the magnetic fields of these two planets are generated. The electrical conductivity of the water-ammonia-methane fluid probably gives a clue and it is thought that convective motions within a thin spherical shell of this fluid might be the source of the ice giants' weird magnetic fields.

Thus far, the two planets do look like identical twins, but on closer inspection a number of differences begin to show.

For one thing, Neptune is a little smaller than Uranus (in rounded figures, 30,000 miles or 50,000 km as against 32,000 miles or 51,000 km for Uranus) but is somewhat more massive. Neptune weighs in at 17 Earth masses as against 15 for Uranus, meaning that Neptune is the denser of the two ice giant planets. A greater difference lies with the axial tilt of the more remote world. Contrasting with the reclining Uranus, Neptune stands relatively straight with a tilt of 28.32°, not greatly more than those of Earth and Mars (23° and 25° respectively). Neptune, therefore, does not share the seasonal craziness of Uranus but goes through seasons not unlike those of Earth and Mars although, of course, on

greatly extended timescales owing to a "year" close to 165 times longer than that of Earth.

One common feature shared by both Neptune and Uranus, ironically, betrays a difference and not a similarity between these two planets. This is the temperature at the nominal surface (i.e. where the atmospheric pressure equals Earth's at sea level). The two planets are equally warm, even though Neptune lies half as far again from the Sun as Uranus and receives only 40 % as much solar radiation. Uranus radiates only a trace more heat than it receives. Neptune radiates about 2.61 times as much. Exactly why this is so is a mystery, but it is possible, as suggested earlier, that the peculiarities of Uranus—the low density, relative lack of internal heat and the extreme axial tilt—are related and may stem from the massive impact which is thought to have occurred early in the life of that planet. The axial tilt is the most obvious result of this, and the lack of such an extreme tilt of Neptune probably indicates that it did not experience a similar impact in its youth. Its development may therefore have been more "normal" for an ice giant just as Venus, rather than Earth, may be a more "normal" terrestrial planet thanks to its apparent avoidance of the sort of collision that is widely believed to have given Earth its Moon.

Neptune also appears to be a stormier place than Uranus and is the site of the strongest winds yet recorded within the Solar System. The Neptunian troposphere, or lower atmosphere where temperatures decrease with altitude, extends to levels where the pressure is one tenth that of Earth's atmosphere at sea level. This marks the tropopause and the beginning of the stratosphere, which in turn gives way to the thermosphere and exosphere. Like the other planets, the troposphere is where the meteorological action takes place. Wild storm systems have been tracked packing winds of some 1,230 miles (2,100 km) per hour! It is thought that several distinct layers of cloud having differing compositions are also present within this zone. The upper layer occurs where pressures are below that at Earth's sea level and consist of methane. Lower down in the atmosphere—at pressures between one and five times that at sea level—ammonia and hydrogen sulfide are believed to form further cloud layers. At pressures of five times sea level there may be clouds of ammonium sulfide, hydrogen sulfide, water and ammonia. High altitude clouds have been seen casting shadows on the

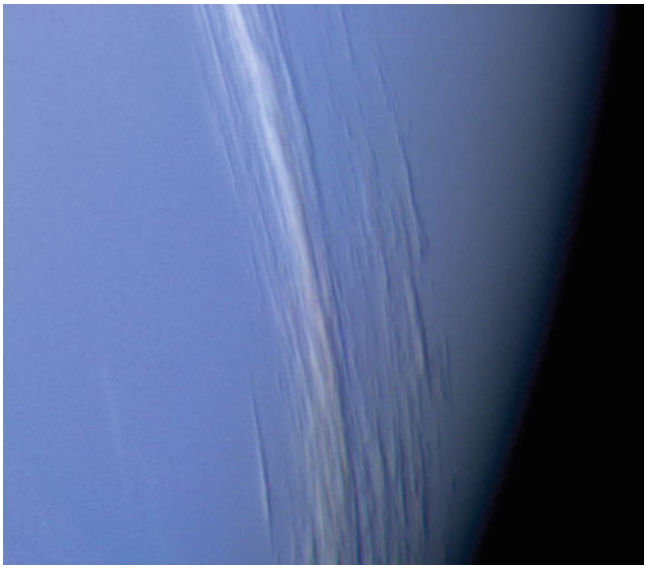


Fig. 2.10 *Clouds* in Neptune's atmosphere (Credit: NASA)

underlying cloud banks and there are bands of the former some 31–94 miles (50–150 km) wide lying about 31–69 miles (50–110 km) above the main cloud deck. These bands circle the planet at constant latitudes. Prevailing (non-storm) winds at the cloud tops vary in velocity from about 870 miles (1,400 km) per hour at the equator to "just" 560 miles (900 km) per hour at the poles. Most of the winds move in the *opposite* direction to Neptune's rotation.

The lower stratosphere is somewhat hazy due to various products, such as ethane and acetylene, arising from the ultraviolet dissociation of methane. Trace amounts of carbon monoxide and hydrogen cyanide have also been found in this atmospheric layer. Despite its much greater distance from the Sun, the stratosphere of Neptune is actually warmer than that of Uranus; a curious finding explained by the higher concentration of hydrocarbons absorbing sunlight and converting it into heat (Fig. 2.10).

Yet Another Ringed Planet!

As soon as the discovery of Neptune was announced, it became the focus of attention for some of the most experienced astronomers of the day. Such was William Lassell, who discovered the

planet's largest moon, Triton, on October 10, just 17 days after the official discovery of the planet itself. However, Triton was not all that Lassell suspected that he had found. On October 3, he wrote in his journal "I observed the planet last night and suspected a ring … but could not verify it." Come nightfall on that same day, he "showed the planet to all my family and certainly tonight have the impression of a ring." Once more, on October 10, he observed the ring and wrote that he could even discern the background sky through it. By then, almost all doubt as to the ring's reality had vanished from his mind—*almost* all doubt, not quite all! His later observations failed to confirm these early ones and his confidence in the ring's reality faded. In the meantime though, several other experienced and skilled astronomers—Dawes, Nasmyth and John Hartnup to cite three prominent names—had "confirmed" the existence of something strongly resembling Saturn's rings when viewed from an edge-on perspective. Another well known astronomer, J. Hind, did not at first detect any ring surrounding the planet, but after it was apparently seen by other observers, he seems to have taken a more careful look and likewise detected something resembling an edge-on ring.

Alas, subsequent history was not kind to the Lassell ring. Later observations of Neptune with larger telescopes (including some made by Lassell himself) failed to confirm its existence and the whole thing just faded away into time. A mixture of preconception and minor flaws in the telescopic optics is now thought responsible for the entire episode (Fig. 2.11).

Nevertheless, the non-existence of the Lassell ring did not close the saga of Neptunian rings in general, although it would be many years before the subject was raised again. Ironically, data suggesting a ring was gathered during an occultation of a star of approximately equal brightness as the planet in 1968, but this went unrecognized until after the Uranian rings were discovered 9 years later. If Uranus had rings, then the possibility of a Neptunian ring system was once again an open question and the 1968 occultation data reexamined. Evidence for what appeared to be a partial ring or arc was found within the data, but it was not definitive. Another occultation took place in 1981 and a Villarova University team led by H. J. Reitsema noted a dip in the star's light while still separated from the planet's disk, suggesting the presence of a ring

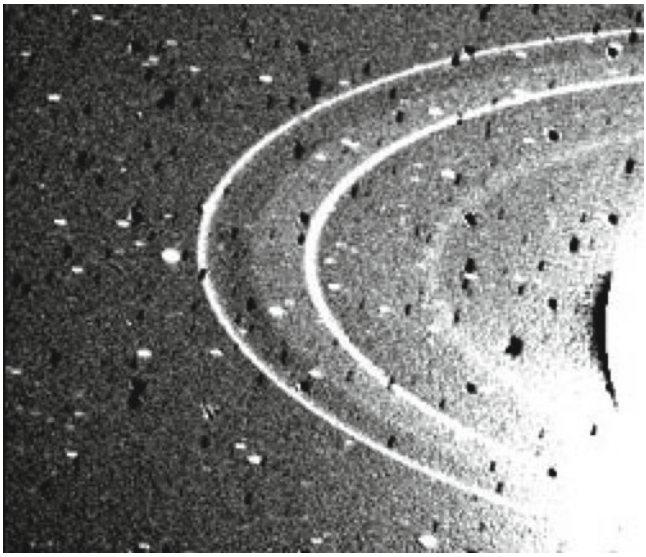


Fig. 2.11 The rings of Neptune (Credit: NASA)

or at the very least a ring arc. This proved not to be so however. What this team had witnessed was a highly improbable event; a secondary occultation by a small and at the time unknown Neptunian moon! This body was later observed by *Voyager* and has since been named Larissa. Careful observation of another occultation on September 12, 1983 suggested a possible ring, but later occultations yielded conflicting results. Some suggested the presence of a ring, others did not. Was this evidence of a broken ring or a system of disconnected ring arcs?

The issue was finally settled when *Voyager* arrived at the planet in 1989 and imaged a definite ring. Subsequently, the ring has also been imaged by the *Hubble Space Telescope*. The rings, as *Voyager* imaged them, are quite faint and have a clumpy structure, possibly indicative of small moons orbiting close to or even within them. The outer ring—the one responsible for the inconsistent occultation results—contains five individual arcs. This is known as the Adams ring, named in honor of the English scientist who mathematically deduced the presence of the planet from perturbations of the orbit of Uranus. It is somewhat ironic then, in view of the rivalry between this Englishman and his French counterpart, that the five arcs comprising this ring should be named Courage,

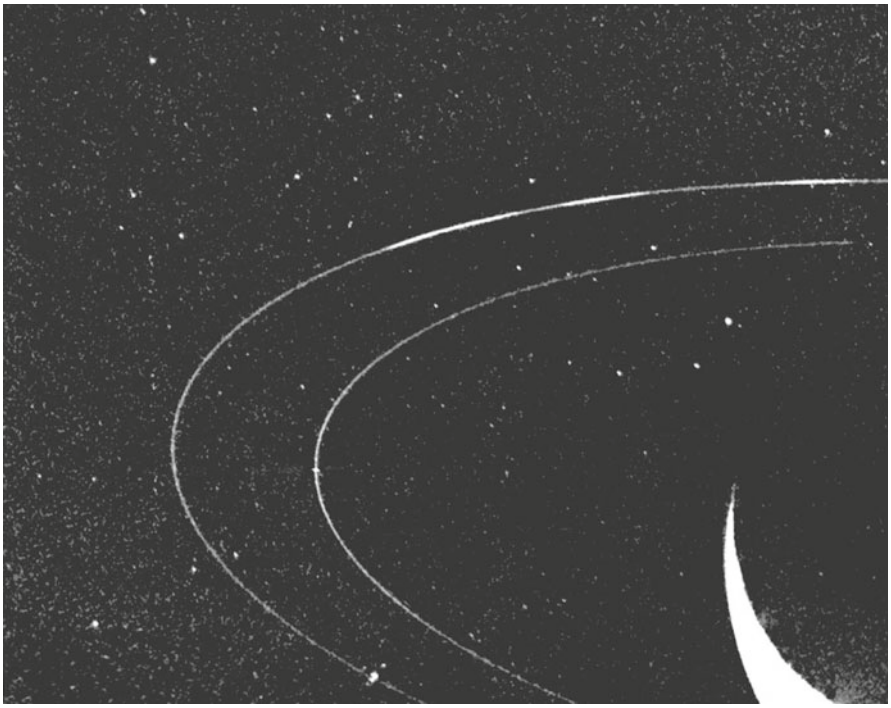


Fig. 2.12 Arcs visible in Neptune's rings (Credit: NASA)

Liberte, Egalite 1, Egalite 2 and Fraternite (Courage, Liberty, Equality and Fraternity)! The arcs initially seemed difficult to explain as one would expect their composite particles to have long ago spread out around their collective orbit and the arcs smeared together into one continuous ring. It now appears that they are kept confined by the gravitational influence of a small shepherd moon orbiting a little distance inward from the ring itself. This moon, known as Galatea, is also responsible for 42 radial "wiggles"—each having an amplitude of about 19 miles (30 km) within the ring. Nevertheless, although Galatea keeps the arcs from quickly disappearing, it can probably not hold back the inevitable for very long. Changes in the ring detected by ground-based observations from W. M. Keck Observatory in 2002 and 2003 suggest that one of the arcs (Liberte) may be gone in as little as 100 years. This further implies that the present form taken by the Adams ring has not existed for long and that the system appears to be very dynamic and in a constant state of flux on timescales as short as centuries (Fig. 2.12).

Contrasting with the Uranian rings, those of Neptune contain a good deal of micron-sized dust particles. In this, they more closely resemble the ring system of Jupiter. The particles appear to be dark and probably consist of a mixture of ice and organic compounds, probably debris from a small disrupted inner satellite of the giant planet. They vary in width from about 60 miles (roughly 100 km) or even less to nearly 3,000 miles (5,000 km). The innermost ring (known as the Galle ring in honor of the planet's discoverer) circles Neptune from 25,600 miles (41,000 km) to nearly 26,900 miles (about 43,000 km) above the planet itself. From these dimensions, it can be seen that this is one of the wider rings in the system. By contrast, the outermost Adams ring has a width of just 9–31 miles (about 15–50 km) and is located almost 40,000 miles (63,930 km) from the planet.

Where Do the Ice Giants Fit in to the Solar System?

One of the weirdest things about the two ice giants is that they are there at all! In the days of astronomical innocence, that is to say prior to the discovery of other solar systems in the 1990s, it was generally assumed that the formation of the Solar System was an orderly and regular event (to suggest anything else smacked of the heresy of catastrophism!) and the planets formed pretty much in the regions where they are located today. On a cursory examination of the System, this did not seem too bad an idea. The portions of the cloud of gas and dust that would become the system of planets should have been thinner closest to the infant Sun thanks to the depletion of dust and volatile materials caused by a combination of solar radiation pressure and higher temperatures in that region. At what we might call "middle distances" the pre-planetary nebula would have been at its densest and cool enough to be rich in volatiles. At large distances, the nebula would have thinned out again, eventually blending into the extremely rarefied matter of interstellar space. Broadly speaking, this seemed to account for the general properties of the Solar System; small and rocky planets closest to the Sun, Gas giants at middle distance decreasing to lesser giants (or ice giants as we now call them) at large distances, dwindling off to diminutive Pluto on the fringes (assuming that

this was not an escaped Neptunian moon; a rather widely held hypothesis last century).

Closer and more detailed examination, however, gave a less satisfactory result. Of particular relevance for us, the ice giants seemed just *too* far away to be readily explained. Assuming (in line with the prevailing orthodoxy of uniformism) that no great disturbing events had occurred to eject these worlds to their remote habitations and that, in consequence, where we see them is where they formed, theorists came up against great difficulties in explaining how they could have grown to be as large as they are. Certainly, they are significantly smaller than Jupiter and Saturn, but it was difficult to see how there could have been sufficient material at their large distances from the Sun to permit the formation of *any* sizable planetary body.

Then, in the final couple of decades of the twentieth century, accepted orthodoxy on these matters fell apart. Pluto, it turned out, was not a fully-fledged planet at all, merely one of a myriad of small bodies, some of which may actually outweigh it. More devastating though, the discovery of other planetary systems brought with it the shocking revelation that our Solar System was not the archetypal model of all planetary systems but just one of countless forms that these systems can assume. And some of these (indeed *most* of these!) looked pretty weird from our perspective. So weird in fact that they failed to fit the regular, uniformist, model that had been widely accepted for decades. The feature of these alien planetary systems that was hardest to fit into the popular model was the existence of so-called "hot Jupiters" or massive gas giant planets orbiting their primary stars at very small distances. There just seemed no way that something as rich in volatiles as Jupiter or its extrasolar equivalent could form closer to its star than Mercury is to our Sun. Yet hot Jupiter after hot Jupiter was being discovered; some so close to their central star as to make the orbit of Mercury look distant by comparison. Not content with that, discoveries of other systems very quickly brought to light another class of planets almost as shocking as the hot Jupiters. These were the "eccentric Jupiters"; gas giants moving through their systems on orbits more reminiscent of those followed by periodic comets within the Sun's family. Clearly, our thinking about the genesis and evolution of planetary systems had to undergo a major readjustment!

This readjustment involved a paradigm change from belief in an orderly evolutionary process to one in which violent, catastrophic, stochastic events played a critical role. Planets did not simply form at one place in a pre-planetary nebula and stay put like obedient children. The process was also far from neat in the sense that there was much material left over after all the planets within a system had formed. Moreover, this material was not to be dismissed as of no importance, nor did it consist entirely of small and insignificant bodies. Much "left-over" material existed in the form of bodies the size of small planets (Pluto-like objects) and even the smaller bodies that numerically made up the lion's share of this material existed in such enormous numbers as to play an important role in the way the entire system turned out in the end. In short, the picture that emerged was one of planetary systems in which planets gravitationally interacted with each other and with the myriad small objects surrounding them to such a degree that some were hurled into interstellar space, some sent crashing into the central star and others caused to migrate inward until they reached distances from their star far smaller than those of any planet in our own Solar System. Yet others experienced such close encounters that the eccentricity of their orbits increased to a degree exhibited only by comets within the Sun's family. There even appeared to be evidence that some of these eccentric planets were the outcomes of planetary collisions and mergers between gas giants.

We will see in the final chapter just how odd some planetary systems and their denizens can be. For now, we simply note that this new understanding of solar systems in general opens up new possibilities for explaining *our* Solar System in particular. Clearly, ours appears a far more orderly place than many; possibly even most. But that apparent orderliness of middle age does not necessarily imply an entirely quiet youth. That was the mistake made by earlier theorists.

Although not universally agreed upon, one model of the Solar System widely accepted today is known as the Nice model (that's "Nice"—rhyming with "fleece"—as in the name of the French city where the model was first put forward, not "nice" as the opposite of "nasty"!). *Very* broadly and *very* briefly, the model may be summarized like this:

The four giant planets initially formed in nearly circular orbits a lot closer to one another than we see them now; from not far beyond the present orbit of Jupiter to beyond that of Saturn, though still well inside the contemporary orbit of Uranus. Beyond these planets millions of small icy bodies—planetesimals—orbited. For convenience, these may be called "comets" although many were considerably larger than the bodies to which this term is normally applied. Pluto-sized objects as well as bodies like the Earth-sized impactor believed to have toppled Uranus onto its side were included in their number, albeit together with multitudes of objects similar to the familiar comets that we know today. Being close to this belt of cometary bodies, Uranus and Neptune frequently encountered some of its members, deflecting many of them inward. Each encounter resulted in a loss of angular momentum for the comet and a gain for the planet and, although each contribution was negligible on its own, the sheer number of encounters meant that both planets gained angular momentum and slowly migrated outward. Comets deflected inward encountered Saturn, with similar results. On the other hand, Jupiter was then, as now, so massive that most bodies reaching its vicinity were deflected outward, ending up either in the distant Oort Cloud (more about this in the following chapter) or in interstellar space, expelled from the Solar System forever. The result was that Jupiter lost some of its angular momentum and migrated inward, although (fortunately for us!) halting its progress well short of joining the ranks of the hot Jupiters that we will meet in Chap. 6.

This slow dynamical evolution eventually brought Jupiter and Saturn into a 1:2 resonance, i.e. each planet moved into an orbit such that one complete revolution of Saturn coincided with two complete revolutions of Jupiter. This meant that the two planets returned to the same configuration after two revolutions of Jupiter and one of Saturn. Once this resonance was reached, things began to happen more speedily. Jupiter shifted Saturn even further outward and this in turn sent Uranus and Neptune into distant orbits of higher eccentricity, where they periodically penetrated into the disk of comets that began this whole process in the first place. These two intruding giants hurled comets every which-way. Many were thrown into the inner Solar System where

they slammed into the Earth and the other rocky bodies in what is known as the Late Heavy Bombardment. Others retreated outward to form the Kuiper Belt. In the process, multitudes of encounters with these bodies reduced the eccentricity of the orbits of Uranus and Neptune (though not their average distances from the Sun) until, having cleared most of the smaller objects from their vicinity, they finally settled down into the orbits in which we find them today (some versions of the Nice model, however, have the two planets swapping places, such that Uranus was originally the most remote planet, but that remains an unsettled question and need not concern us here).

An ironic consequence of this model, or any recognizable variation thereof, is the unexpectedly important role played by minor bodies in the evolution of a planetary system. Traditionally, minor bodies such as comets and asteroids have been dismissed as almost unworthy of study, except for a small band of astronomers who found themselves drawn to this rather unfashionable subject. Percival Lowell, for example, dismissed comets as "bagfuls of nothing" and Patrick Moore as "[sometimes] striking, but … not very important" while Gauss, as we shall see in the following chapter, disparagingly described asteroids as "clods of dirt" while the expression "vermin of the skies" was heard on the lips of other astronomers in reference to both asteroids and comets. But if the Nice model is correct, the fate of planetary systems depends to a large degree on the number of comets and similar minor bodies whose formation precedes that of the planets themselves and of which those very planets are ultimately formed.

The Nice model, as it stands, is not perfect. For instance, the detailed structure of the Kuiper Belt has not been reproduced by any version yet put forward, but it does account for most of the features of the Sun's family and the correct model of this system will likely fall within its overall parameters. In particular, the presence and positions of the ice giants is accounted for in a way that earlier models could not accomplish and the broad structure of the Solar System itself explained in terms of various processes that appear to have sculptured every planetary system discovered to date. Only after finding other systems of worlds and discovering that they were far from being clones of our own,

did the way open for models such as this and any real hope of a satisfactory account of the evolution of the Sun's planetary family made possible. It was the very weirdness of these alien systems that provided the key to unlock a greater understanding of our own!



http://www.springer.com/978-1-4614-7063-2

Weird Worlds
Bizarre Bodies of the Solar System and Beyond
Seargent, D.A.J.
2013, XIII, 309 p. 51 illus., 23 illus. in color., Softcover
ISBN: 978-1-4614-7063-2