VOYAGER: A RETROSPECTIVE

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ABSTRACT. Within the brief span of a decade, from 1979 to 1989, the Voyager spacecraft visited the four giant planets – Jupiter, Saturn, Uranus and Neptune – along with their satellites and their rings. The science return from these two spacecraft forever changed our views of this remote region of our solar system. Often overlooked, however, is the incremental gain in knowledge from these encounters over that which had been known in the early 1970s when the Voyager project first came into being. From a post-Voyager perspective, it is astonishing how little was known about the outer planets just a mere two decades ago. Yet, with all of the knowledge that the space program has brought us, there remain a number of unanswered questions and a great many new ones that have been posed as a result of this wealth of new information. Discussed here is summary of the results of the Voyager imaging cameras together with some of the many new questions that subsequently have been raised.

1. Introduction

It was nearly two decades ago that we, as a community of scientists, reluctantly turned our backs on human exploration of the moon and turned our expectations to the outer solar system. Preparations were then being made to launch two Pioneer spacecraft to Jupiter, and planning was well underway for a "Grand Tour" of the entire outer solar system, making use of a rare planetary alignment that would take place in the year 1977. The fiscal realities of the times, however, soon caused the Grand Tour to be scaled back to a much more modest mission, one that would explore only the two most accessible of the outer planets. On July 1st, 1972, Mariner Jupiter/Saturn, or MJS as it was called, became an approved NASA project, and within six months, even as the Apollo 17 astronauts were bidding a final farewell to the moon, the first of the MJS science planning meetings was already taking place.

Our keen disappointment in the cutback, which might otherwise have dampened those early meetings, was mitigated by the knowledge that *any* spacecraft launched on the right Jupiter-Saturn trajectory in 1977 would also have the capability of continuing onward to both Uranus and Neptune, a fact that may or may not have been understood by the administrative and legislative committees that killed the Grand Tour and substituted MJS. Two identical Mariner-class spacecraft were to be sent to Jupiter and Saturn, and throughout our five years of planning, we carefully held open all options for at least one of them to go beyond. In 1977, just before launch, MJS was renamed Voyager, but it was only *after* launch that the official approval was given to send Voyager 2 onward from Saturn out to Uranus and Neptune.

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As we now look back from our post-Voyager perspective, it's truly astonishing how little we knew about the outer planets just a mere two decades ago. We were well aware, of course, of such fundamental properties as their orbital elements and their approximate size and mass. Their densities suggested that they were made up mostly of hydrogen and helium, but knowledge of their interior structure was in a very poor state. We knew that Uranus rolled along on its side, but we could not even guess the length of its day nor that of Neptune. In fact, we didn't know whether Neptune's rotation was direct or retrograde or, for that matter, just where its spin axis was pointed. Methane and hydrogen had been detected in all of the atmospheres, and ammonia had been found in those of Jupiter and Saturn. Jupiter alone was known to possess a magnetic field and to radiate more energy than it absorbed from the sun. Jupiter's Great Red Spot was recognized as an enormous anticyclone, but we had seen only a very few cloud features in Saturn's atmosphere and none at all on Uranus and Neptune. We knew that Titan, Saturn's largest satellite, had an atmosphere containing methane, but we mistakenly thought that Jupiter's Galilean satellites might also have thin atmospheres. Just what geological features might exist on the surface of any satellite was mere speculation. In fact, only 29 of the 58 outer solar system satellites known today had even been found at that time. Saturn was the only planet known to have rings, and we had quite acceptable theories to explain why none of the other planets could *possibly* have them. Textbooks devoted but a half dozen or so pages to the entire outer solar system, and most of that dealt with the clouds on Jupiter, the rings of Saturn and the discoveries of Uranus, Neptune and Pluto.

But new technologies were becoming available to astronomers in the late '70s and early '80s, and even as the two Voyager spacecraft were being fabricated and were later sailing outward toward their destinations, important discoveries were being made. Earthbound telescopes found a thirteenth satellite of Jupiter and added four more for Saturn. Water was detected in Jupiter's atmosphere and ethane, ethylene and acetylene in Saturn's. Saturn was found to have an internal heat source even more impressive than that of Jupiter. In 1977, the discovery of nine narrow dark rings around Uranus deprived Saturn of its unique status and confounded the specialists in ring dynamics. Clouds carried by zonal winds were observed in Neptune's atmosphere and methane was detected on Triton. However, just as the dynamicists were making progress with the Uranus rings, they lost ground again when dark ring segments, or "arcs" as they were called, were discovered around Neptune. Triton was believed for a while to be the solar system's largest satellite and some suggested that it might have liquid nitrogen oceans.

Many of the most important pre-Voyager discoveries in the Jupiter and Saturn systems, however, came from Voyager's predecessor, Pioneer. These reconnaissance spacecraft found intense belts of radiation around Jupiter and made important contributions to our understanding of its magnetosphere and gravitational harmonics. One of the two Pioneer spacecraft was sent onward from Jupiter to Saturn where it found a new ring – designated the F ring – just outside the bright ring system and mapped Saturn's radiation belts and magnetic field. Occultations of Pioneer's radio signals yielded density profiles of the Jupiter and Saturn atmospheres. But Pioneer was limited by its spin-stabilized design and its instrument payload and could tell us little else about the atmospheres of Jupiter and Saturn – and almost nothing about their satellites.

The intensity of the Jovian radiation belts surprised everyone. Pioneer was nearly destroyed, and Voyager, far more sophisticated and therefore more vulnerable, had to be redesigned with electronic and optical components that were radiation hardened.

By 1977, Voyager was – just barely – ready for launch. It was a three-axis stabilized spacecraft carrying 11 scientific experiments, including two cameras, ultraviolet and infrared spectrometers, a photopolarimeter, a radio experiment, and charged particle and magnetic field detectors.

Voyager 2 was launched on August 20th, and Voyager 1 followed nearly two weeks later on a faster track to Jupiter. Launching Voyager 2 first and sending it on to a later arrival at both Jupiter and Saturn was all part of the strategy to preserve a Uranus/Neptune option. Shortly after launch, Voyager 1 looked back and took an historic picture of our Earth and Moon, seen together for the first time as a unique planetary system. This view of a blue and white "quarter Earth" and a smaller, darker "quarter Moon" was Voyager's first picture from space. More than twelve years would pass before the Voyager cameras would again look back toward Earth.

The two Voyager spacecraft arrived at Jupiter less than two years after launch in 1979. Voyager 1 reached Saturn in 1980 and then began its long journey out of our solar system. Voyager 2 arrived at Saturn in 1981 and then, in spite of grave concerns over its health and longevity, continued its successful mission, flying by Uranus in 1986 and finally reaching Neptune in 1989. Over the decade from 1979 to 1989, these two interplanetary travelers changed forever our view of the giant planets, rings and satellites of outer solar system.

That Voyager surprised us again and again is in itself not surprising. Our poor understanding of the outer planets and their physical environment often led us to make predictions that, in retrospect, were at best naive and, in some cases, outright embarrassing. For example, once we knew with certainty that Io was volcanically active, we began looking for trailing volcanic plumes much as we might see on Earth, failing to realize in our excitement that Io does not possess a sensible atmosphere and that the morphology of volcanic plumes would be very different on an airless body. Ten years later, incidentally, we *would* see Earth-like volcanic plumes, but they would be on Triton at the very edge of our planetary system. We were also mistaken in believing that the structure of the Saturn ring system would be rather simple and straightforward, and so we scheduled relatively few ring observations with Voyager 2, on the assumption that we would have learned nearly everything during the Voyager 1 encounter. The rings turned out to be anything but simple. Even after hurriedly redesigning the Voyager 2 ring sequences, there is much that we still do not understand about this extremely complex ring system.

As with any highly successful scientific experiment, the Voyager instruments provided answers to most of the questions we had raised about the physical nature of the outer solar system. But, in so doing, it also posed many new questions – more, in fact, than we had raised to begin with.

It would not be possible to summarize the results of all of the Voyager instruments here; I will therefore confine my discussion to those with which I am most familiar, the imaging results. So, with this introduction, I will now summarize some highlights of the Voyager imaging discoveries, show how they have changed our understanding and point out what is still unknown about this remote region which contains more than 99 percent of all the non-solar mass in our solar system.

2. The Giant Planets

2.1. JUPITER

The complexity of the structure and dynamics of the Jovian atmosphere turned out to be far greater than our groundbased experience had prepared us for. Rather than a simple system of zonal flow in the banded structure with embedded vortical circulation in the Great Red Spot (GRS) and White Ovals (WO), we found that vorticity was to be found at every size scale down to our limit of resolution. Extraordinary complexity existed within the GRS and the immediate surroundings of the zonal currents in which it is situated. For, example, white clouds would approach the GRS, only to be caught up in its vortex. At this point, they would circulate around the perimeter of the GRS and either be thrown out after a revolution or two or be incorporated into the GRS itself. One such feature was observed to split in two, with one component be ejected and the other assimilated. Other examples of bizarre behavior were observed in the mutual interaction of small vortices in the North Temperate Zone. These features could be seen to approach one another, circle each other in a sort of *pas de deux*, then separate and continue along their respective ways.

Much is now known about Jovian global circulation. We have been able to show, for example, that the global zonal flow is derived from buoyant convective eddies, such as the GRS and WOs, rather than *vice versa*. We know that most of the bright atmospheric clouds at all scales are actually anticyclones like the GRS. The complete dynamical picture, however, is very far from being complete. To truly understand this complex system would require an orbiting satellite making synoptic meteorological observations over a period of several decades.

A long exposure made of the nighttime hemisphere revealed three layers of auroral arcs at levels from 700 to 2300 km above cloud tops and recorded a dozen or more lightning bolts with energies of 10^{10} j, equivalent to the cloudtop superbolts of the terrestrial tropics. The brightness of the nighttime illumination from the rings, however, made such observations impossible at Saturn and limited data rates prevented us from scheduling nighttime observations of Uranus and Neptune. We can only suppose that lightning must exist in the atmospheres of these other planets as well.

2.2. SATURN

In 1979, just a few months after Voyager 2's encounter with Jupiter, Pioneer flew past Saturn. Its failure to show any discrete atmospheric clouds in Saturn's atmosphere caused considerable concern among Voyager atmospheric scientists. Such features would be absolutely necessary for use as tracers of Saturn's atmospheric circulation. Fortunately, the problem was merely one of instrumentation. The intrinsically lower contrast of the Saturn clouds proved to be too difficult for the limited dynamic range of the Pioneer camera. The mid latitudes of the Saturn atmosphere were, like those of Jupiter, dominated by anticyclones at all scales from 5000 km on down to the limit of resolution. Moreover, we could see both cyclones and anticyclones nested within the wave crests and troughs of a northern hemisphere jet stream. This dynamical behavior is quite similar to that of the terrestrial atmosphere, except that the terrestrial jets characteristically have 4-6 waves and this particular Saturn jet had nearly two dozen. The study of similar dynamical phenomena on diverse planetary bodies can hopefully lead to increased understanding of the processes taking place on all of them

As with Jupiter, we were able to characterize the global circulation of Saturn's atmosphere and found it to be generally similar to that of Jupiter. But certain basic differences were evident. For example, unlike that of Jupiter, the atmospheric albedo banding was not correlated with the boundaries of global zonal flow. Saturn's equatorial jet was also much wider and more intense than that of Jupiter, with wind speeds of up to 450 m/sec.

Both spacial and temporal resolution was lower at Saturn than at Jupiter. Nevertheless, it was clear that the small-scale structure of Saturn's atmosphere was equally complex in both its structure and dynamics and that we still have only the very poorest understanding of this barely discernable regime.

2.3. URANUS

For Voyager's imaging atmospheric scientists, Uranus was a great disappointment. Convective clouds lay hidden beneath and obscured by the strong Rayleigh scattering of a transparent, but very deep, atmosphere. But, like Jupiter and Saturn, the overall appearance was axisymmetric ,with dark and light bands parallel to the planet's equator. This came as a surprise to many, who had not expected this well-defined zonal pattern in the global circulation of a planet with such high obliquity, a negligible internal heat source and relatively slow rotation. It emphasized that coriolis forces continue to play a dominant role in atmospheric circulation, even under conditions of highly asymmetric solar insulation. The south polar region was covered with a hood of orange colored cloud, presumably a photochemical smog.

The atmosphere, fortunately, was not completely devoid of discrete features. A few very high clouds were visible in the sub-polar and mid southern latitudes, perhaps composed of methane or photochemical condensates or of interplanetary dust. These few clouds permitted the global circulation to be mapped, although not nearly as well as we had hoped. Although no clouds were seen at the equator, the measured winds at other latitudes showed monotonically increasing westerly wind speeds from about 20°S to 70°S. Improved knowledge of the global circulation of the Uranus atmosphere may now be possible though improved groundbased imaging techniques

2.4. NEPTUNE

With a trend toward decreasing visibility of discrete atmospheric clouds as we moved outward from Jupiter to Saturn to Uranus, the outlook for Neptune was anything but promising. Yet, some optimism prevailed. In 1979, groundbased imaging of Neptune, taken within far-red methane absorption bands, had revealed relatively high contrast bright features on the 2.3-arcsec disk, and it was hoped that these clouds would have sufficiently high contrast to be visible with Voyager's cameras. It came as a great relief when the first distant Voyager images revealed several of these bright clouds.

By this time, it came as no great surprise that Neptune has the same axisymmetric banded pattern as the other giant planets. But there were certainly surprises in the detailed appearance. An enormous vortex was observed in Neptune's south tropical region, bearing a strong resemblance to Jupiter's Great Red Spot, except that it was dark gray, not red. Naturally, it became known as the Great Dark Spot (GDS). The GDS also is an anticyclone, an oblate dynamical system measuring 6000 by 16000 km, on the average. Curiously, it is in the same hemisphere and at nearly the same latitude as Jupiter's GRS and has the same size and shape relative to the size of the planet. But, whereas the GRS is relatively stable in appearance over an interval of several weeks, the GDS changes both its size and shape on time scales of just a day or so. Another significant difference is that the vorticity of the GDS is less than that of the ambient sheer, just the opposite of the case for the GRS. Otherwise, the details of its vorticity are much more poorly known than that of the GRS, a consequence of the lack of observed interaction with other atmospheric features at the same latitudes.

A curious and poorly understood result of the atmospheric study is that the pattern of global circulation of Neptune is closer to that of Uranus than Jupiter or Saturn, despite Neptune's obliquity and internal heat source being much closer to that of Jupiter and Saturn. In the case of Neptune, all zonal winds were easterly, except at high latitudes,whereas the Uranus winds are westerly. But this is more a matter of different offsets from the planetary frames of rotation This offset produces a strong equatorial jet in Neptune's atmosphere with winds of -600 m/sec.

As with Jupiter, highly bizarre behavior was observed in certain dynamical regimes in Neptune's atmosphere. At one point, a great dark cloud was seen to issue from the leading end of the GDS, thinning as it extended in length and ultimately breaking down into a series of small dark clouds, appearing much like beads on a string. Unfortunately, Voyager crossed over to the dark hemisphere of Neptune before the final outcome of this remarkable event could be recorded. In other instances, vortices were observed to make rapid changes in

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latitude with corresponding changes in zonal velocity, a phenomenon not seen on either Jupiter or Saturn.

The upper atmosphere of Neptune was extremely clear. High clouds could be seen to cast shadows on a lower cloud deck some 100 km below. Nothing of this sort had been seen on any of the other giant planets.

3. The Satellites of the Giant Planets

3.1. THE SATELLITES OF JUPITER

Jupiter is now known to have 16 satellites, 3 of them discovered by Voyager; but, the greatest scientific interest by far has been directed toward only four of them, the Galilean satellites. All are planetary size bodies in their own right. The smallest among them is only a little smaller than the Moon and the largest is even larger than Mercury.

Callisto presented to us an ancient mantle of ice, covered with a thin, dark, surface layer of interplanetary or circumplanetary dust. Impact features stood out clearly as bright, white ice excavated by the colliding body. Valhalla, a ghost-like impact basin more than 3000 km in diameter, remains as a visible scar of one of the last large planetesimals to be incorporated into this outermost of the Galilean satellites.

Only slighter bigger than Callisto, Jupiter's largest satellite, Ganemede, has had a very different history. Evidence of early tectonic processes abounds. A strange terrain composed of parallel grooves, tens of km wide and hundreds of km long, indicates an era of extensive plate movement in the ice mantle, probably very early in its history. Just why two bodies of nearly identical size ,location and environment should have such different evolutionary histories remains an unanswered question more than a decade after the Voyager encounter.

Europa, the smallest of the Galilean satellites, has the smoothest surface of any known solar system body. It was only bad luck that, through trajectory selection, this fascinating object was somewhat arbitrarily chosen to receive the poorest resolution of any the Galilean satellites. The highest topography, a series of interconnected ridges, rises no more than 100 m above its smooth icy surface. Although most are more or less straight, there is a network of ridges with a curious curvilinear shape, approximating the function (sin x)/x. Widespread dark linear features,which may be cracks in the ice.mantle, show no relief at even the highest spacial resolution. Below the icy surface of Europa may be the only large volume of liquid water anywhere in the solar system other than Earth.

Io was to have been our Rosetta stone for calibrating meteoritic fluxes in the outer solar system – an ice-free, reddish, sulfur dusted version of our own Moon. But such was not to be! As the images became ever clearer during the approach, curious quasi-circular features became visible, but they were quite obviously not impact craters. As the resolution improved, the strange features increased in number, but still no impact craters were to be seen. It was only when Voyager was nearly upon Io that we recognized we were looking at volcanic features – calderas, lava flows and molten sulfur lakes. But still, no craters were seen, even at the very highest resolution of about a km. Io, therefore, had to be the most volcanically active place in the solar system, where even the most frequent small meteoritic impacts are quickly covered by volcanic flows and eruptive fallout. It was only after encounter when, in looking back, we realized that this activity had been going on right if front of us. Volcanic plumes, reaching 300 km above the surface, rained sulfur particles over the surface. At high latitudes, sulfur dioxide snow covered much of the reddish landscape. It was a world of sulfur and sulfur dioxide driven volcanism, not the familiar molten silicate and water variety that we experience on the terrestrial planets There can be few places seen by the Voyager cameras that are more interesting than Io.

3.2. THE SATELLITES OF SATURN

Saturn is now known to have 18 satellites, 4 of them discovered by Voyager. Most are relatively small bodies composed primarily of water ice.

With an atmosphere more massive than Earth's, a surface pressure and temperature of 1.5 bars and 94K, Titan was the largest and most interesting satellite in the Saturn system. Its atmosphere of nitrogen and more than a dozen other constituents – mostly organic – made it a prime target for Voyager instruments. Unfortunately, its thick cloud cover prevented our cameras from seeing anything more than the highest hazes in its atmosphere. We were successful in recording several high layers of what are most probably photochemical products, complex organic compounds which must eventually rain out and be preserved indefinitely on Titan's frigid surface. Such materials may eventually contribute significantly to our understanding of the prebiotic chemistry that took place on Earth billions of years ago.

Even ice satellites can yield surprises. The largest among them, Rhea, Dione and Tethys, show evidence for internal activity – scarps and valleys that may have been formed long ago from expansion due to freezing. Impact craters are well preserved in the ice, even over several eons. Ice at such cold temperatures has the rigidity of steel.

Since it was first noticed more than a century ago, Iapetus has a highly asymmetric surface albedo. Its leading side reflects only 3% of the sunlight falling on it while the trailing side shines brightly with 50% reflectivity. Whether this dichotomy is due to exogenic or endogenic processes, e.g., a coating of infalling dust or resurfacing by internally erupted dark material, remains unanswered. The poor resolution caused by the unfavorable orbital position of Iapetus at the times of encounter of both spacecraft is one of the great disappointments of the Voyager mission.

Of the remaining small icy satellites of Saturn, it is perhaps worthwhile commenting on Enceladus. Situated in the midst of Saturn's tenuous E ring, it had been thought that Enceladus must somehow be a replenishing source for the tiny, short-lived ring particles. This hypothesis gained a measure of support when the Voyager images of Enceladus showed a region completely void of any impact craters, strongly implying volcanic resurfacing. If so, this must be volcanism based on water alone, a still different type than that of Io or the terrestrial planets. Unlike the previous cases, however, the energy source for the Enceladus volcanism has not yet been identified.

3.3. THE SATELLITES OF URANUS

If the bland Uranus atmosphere was disappointing to the Voyager imaging scientists, the satellites more than made up for it. Of the 15 known satellites, no less than 10 were discovered by Voyager.

The larger of the satellites are similar in size to the larger icy Saturn satellites, but their appearance is very different. Dark material can be seen which has oozed onto the crater floors of Oberon and Titania. Titania and Ariel show evidence for extensive tectonic activity and even erosional valleys and stream beds caused by some kind of liquid flow. Umbrial, however, situated between Titania and Ariel, had a much lower surface albedo than its neighbors and showed no evidence for active surface processes. Just why Umbriel's icy surface should be dusted with dark material that somehow failed to coat Titania and Ariel remains a mystery, as does the sources of energy for the tectonic activity on the two other satellites.

The most bizarre object in the Uranus system is undoubtedly Miranda; with a diameter of only 470 km, it is the smallest of the previously known satellites. Highly varied terrains, from ancient to strongly modified, were seen in juxtaposition with separations of scarcely a few hundred meters. Scarps dropped nearly vertically for distances of 10 to 15 km. In many respects, Miranda looks like a planet that had been either broken up and reassembled or frozen in the process of breaking up. Whatever their origins might be, the geological terrains of Miranda provide a collective sampling of the various terrains found on nearly every other solid body in the solar system.

The small new satellites of Uranus are very dark, with reflectivities of about 5%. Their composition is reminiscent of the very dark material first seen on Iapetus and later on the crater floors of the larger Uranus satellites and the Uranus rings. Too dark for silicate, this is probably the same organic-rich carbonaceous material, which seems to be ubiquitous in comets and throughout the outermost regions of the solar system.

3.4. THE SATELLITES OF NEPTUNE

Neptune has 8 known satellites, 6 of them discovered by Voyager. With the exception of Triton, the largest, they are all very dark, like the small satellites of Uranus.

Triton was the final and the most distant object to be visited by Voyager – and certainly one of the most interesting. With a surface temperature of only 38K, it is the coldest place yet found in the solar system, and is the only satellite other than Titan with a sensible atmosphere. Although the surface pressure is only 10-20 μbars, there is sufficient atmosphere to produce clouds and hazes and to seasonally redistribute volatiles, such as methane and nitrogen.

The underlying surface structure of Triton appeared very similar to that of the Moon, with many large impact features flooded by lavas. As with the Moon, this indicates episodes of heating and surface activity at some time in Triton's distant past. The major difference between the two bodies is that on Triton these now frozen lavas are water ice rather than silicates. These and other tectonic features on Triton point to a traumatic past, probably during circularization of its retrograde orbit following its capture into a highly elliptical orbit.

By far the greatest surprise at Triton was finding active volcanism on this frigid and most distant body. Long streaks of what appeared to be dark, windblown dust had been seen on the surface, implying some kind of active process, but it was stereographic imaging that finally showed at least two eruptive columns, 8-10 km high, with long plume clouds trailed out by the prevailing winds. The most likely volatile involved in the volcanism is nitrogen, which can exist in liquid phase only at subterranean pressures. Thus, still another form of volcanism had been found – this in an environment less than 40° above absolute zero.

4. Rings of the Giant Planets

4.1. THE JUPITER RING SYSTEM

The discovery of the Uranus rings just before the launch of Voyager prompted us to make a search, albeit halfheartedly, for possible rings around Jupiter. Only two frames were allocated for this search with Voyager 1 and none at all for Voyager 2. Most of us had already forgotten about scheduling those frames when the first images of the tenuous Jupiter ring came back from the spacecraft. The observing sequence for Voyager 2, scheduled to arrive at Jupiter in only four months, was immediately modified to include additional imaging of the unexpected rings. The deceptively intricate Jupiter ring system seemed to be composed of dust, quite possibly silicate or sulfur eruptive products from Io. The distribution of the material is probably governed by two of the new satellites discovered by Voyager, Metis and Adrastea, which are actually imbedded in the denser parts of the ring system. Interaction of charged dust particles with Jupiter's magnetic field produces a ring halo which extends well out of the equatorial plane.

4.2. THE SATURN RING SYSTEM

Among the four ring systems of the Outer Planets, that of Saturn is by far the most complex. The B ring itself is composed of perhaps tens of thousands of individual ringlets, spiral bending waves – in which the very thin ring plane is warped by many times the ring thickness – and spiral density waves. While some of the wave phenomena can be attributed to known satellite resonances, the cause of most of the fine structure in the B ring is still unknown.

The Cassini Division revealed more structure than had been known in the entire ring system prior to Voyager. At one time, project personnel considered flying Pioneer Saturn through this "gap". Had they gone through with this plan, the spacecraft would certainly have met an early and premature death.

The outer edge of the A ring was found to be exceedingly sharp, with no detectable outward diffusion of ring particles. This edge is held in place by resonances with the small co-orbital satellites,Janus and Epimetheus, a nearby pair which actually exchange orbits and which must at one time have been a single object.

The optically thin C ring contains one of several eccentric ringlets found in the Saturn ring system. Although difficult to see from the Earth, the C ring shone in brilliant splendor when seen by transmitted light from the dark side of the ring plane.

The Voyager cameras found an even fainter ring just inside the C ring. Although very difficult to see in the glare of light from the planet, its identity was confirmed by the appearance of the planet's shadow edge on the ring. This D ring had been "discovered" in 1969 by Pierre Guerin at Pic du Midi, and was confidently confirmed by myself a year later. The real ring, however, turned out to be very much fainter than Guerin's and could not possibly have been seen with groundbased telescopes. I am now compelled to believe that Guerin's and my observations were entirely spurious.

One of many surprises we received from the Saturn rings was the structure of the F ring, which had been discovered by Pioneer Saturn only a year earlier. The F ring was seen in places to be broken down into several individual strands of irregular shape. This curious distortion is now known to be caused by perturbations from two small shepherding satellites, Prometheus and Pandora, which orbit just inside and outside the ring.

Among the more poorly understood phenomena in all planetary ring systems, perhaps the most baffling and the one which attracted the most attention involves the radial spoke-like features seen in Saturn's B ring. The spokes were observed to revolve at approximately Keplerian rate along with the ring particles for approximately half a revolution around the planet. None were seen to survive more than a half revolution. During this interval of visibility, their shape would often evolve, becoming more elongated in the radial direction with time. The spokes appeared dark relative to the B ring at small phase angles and bright at large phase angles, suggesting micron-size, forward scattering particles. The dynamical behavior suggested charged particles under the influence of Lorentz forces. While the electrodynamics of particles suspended in a plasma cloud tends to fit the observed phenomenon, the question of the origin of the multiple plasma clouds needed to explain the dozens of spokes visible at any one time remains unanswered.

4.3. THE URANUS RING SYSTEM

The Uranus ring system had been extensively studied through groundbased stellar occultations and imaged both in the visible and infrared from the ground. Thus, both the radial structure of these narrow rings and the very low albedo of the ring particles was known before the arrival of Voyager. The major contributions of the Voyager cameras were the early discovery of an optically thin, narrow tenth ring and, following encounter, the detection of a great number of additional rings, both broad and narrow, of exceedingly low optical depth and small particle

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size, such that they could be seen only by forward scattering at very high phase angles. This distribution of fine material between the ten principal rings, raises questions about the age and lifetime of the Uranus rings and, correspondingly, of other ring systems as well. The small inter-ring particles are strongly subject to non-gravitational forces and therefore have relatively short lifetimes. This problem is further exacerbated by the highly extended upper atmosphere of Uranus which reaches all the way out to the ring system, adding drag to the other non-gravitational forces. Thus, it appears that mass is being lost from the ring system at a rate which may not permit its continuous existence over the age of the solar system – just another sticky problem to be raised by Voyager.

4.4. THE NEPTUNE RING SYSTEM

The discovery, by groundbased stellar occultations, of strange arc-like ring segments orbiting Neptune heightened the excitement of Voyager's final encounter. Analysts of the groundbased data were in general disagreement as to the number and radial distribution of the arcs, and this in turn placed strong constraints on the selection of the specific trajectory to be taken by spacecraft as it went past Neptune. Project management did not want Voyager to collide with some errant arc. As it turned out, however, all of the arcs – 3 to 5 of them, depending on how they are defined – were situated in the outermost of 4 to 5 Neptune rings, the total number again depending upon definition. The arcs themselves were seen to be merely condensations in an otherwise continuous ring of low optical thickness. What causes these condensations and maintains their stability against destruction by Keplerian shear is, of course, another matter. Recent studies suggest obscure resonances with the nearby small satellite, Galatea. Like the Uranus rings, those of Neptune are composed of particles having very low albedo, suggesting organically-rich carbonaceous material.

Although all of the Outer Planet ring systems have their similarities, they are in most ways quite different from one another. Why this should be so, whether due to composition, satellite distribution, age or just chance, is one of the more fundamental questions that Voyager has raised.

5. Epilogue

The very first and very last pictures taken by Voyager 1 were of the Earth, the first recorded just a few days after launch, and the last in early 1990 from a distance greater than 40 au, more than 6 billion km away and 32° above the ecliptic plane. In this final departing image, the Earth is seen as a but small blue dot imbedded in a refracted ray of sunlight, a reminder of how far into space Voyager had taken us and our vision of worlds previously unseen.

Both Voyager spacecraft are now in the final phase of the mission, as they race away from the Sun, the Earth and their Creators in search of the elusive heliopause and true interstellar space.