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Planetary Rings

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Abstract. The past two decades have witnessed dramatic changes in our view and understanding of planetary rings. We now know that each of the giant planets in the Solar System possesses a complex and unique ring system. Recent studies have identified complex gravitational interactions between the rings and their retinues of attendant satellites. Among the four known ring systems, we see elegant examples of Lindblad and corotation resonances (first invoked in the context of galactic disks), electromagnetic resonances, spiral density waves and bending waves, narrow ringlets which exhibit internal modes due to collective instabilities, sharp-edged gaps maintained via tidal torques from embedded moonlets, and tenuous dust belts created by meteoroid impact onto, or collisions between, parent bodies. Yet, as far as we have come, our understanding is far from complete. The fundamental questions confronting ring scientists at the beginning of the twenty-first century are those regarding the origin, age and evolution of the various ring systems, in the broadest context. Understanding the origin and age requires us to know the current ring properties, and to understand the dominant evolutionary processes and how they influence ring properties. Here we discuss a prioritized list of the key questions, the answers to which would provide the greatest improvement in our understanding of planetary rings. We then outline the initiatives, missions, and other supporting activities needed to address those questions, and recommend priorities for the coming decade in planetary ring science.

EXECUTIVE SUMMARY

The discovery of the narrow, dark rings of Uranus (1977) was followed by the first Voyager images of the tenuous Jovian ring system (1979), and the spectacular data of many kinds returned during the twin Voyager flybys of Saturn (1980, 1981). In subsequent years, ground-based stellar occultations, the Voyager flybys of Uranus (1986) and Neptune (1989), a handful of Galileo images, coupled with ground-based and HST observations continuing to the present, have defined planetary rings as a class of objects which broadened our perspective and stretched our theories to operate in different environments and regimes. The focus remains on the physics responsible for the phenomena we observe, as well as the basic need to understand the origin and evolution of planetary rings in the general context.

Perhaps the greatest surprise was the complexity and variety of structure in the various ring systems revealed in the Voyager images and occultations. Recent studies have identified complex gravitational interactions between the rings and their retinues of attendant satellites. Among the four known ring systems, we see elegant examples of Lindblad and corotation resonances (first invoked in the context of galactic disks), electromagnetic resonances, spiral density waves and bending waves, narrow ringlets which exhibit internal modes due to collective instabilities, sharp-edged gaps maintained via tidal torques from embedded moonlets, and tenuous dust belts created by meteoroid impact onto, or collisions between, parent bodies. We are starting to realize that bombardment of rings by interplanetary meteoroids can have very significant effects on both ring structure and ring composition. Studies of planetary rings have increased our understanding of the behavior of astronomical disks in general and have been fundamental in improving our understanding of nebular dynamics and extrasolar planets.

Nonetheless there remain many unresolved issues in our attempt to establish the origins and ages of the various ring systems. One glaring unresolved problem is identifying the mechanism(s) that produce the "record-groove" structure pervading Saturn's dense rings. Another major unsolved puzzle is Saturn's multi-stranded, clumpy F ring, which continues to defy a simple explanation more than twenty years after it was first glimpsed in grainy images taken by Pioneer 11. The composition of planetary rings remains a major unknown, beyond some zero-order understanding. While only Saturn has a substantial system of dense rings, all four giant planets maintain rings of fine dust, yet none of the inner planets appears to support an equivalent ring system. As we continue to study planetary rings we will continue to identify similarities and differences that may ultimately provide insight into the processes that produce, modify, and maintain ring systems.

Finally, one unanticipated realization has been that all ring systems may be much younger than their parent planets. That is, the processes by which they evolve are so vigorous that they are hard to reconcile with primordial ages. This raises the so called "short timescale" problem, most serious for Saturn's rings. Are we just lucky to be living in the "age of rings"? How is it possible to create a ring system as massive as Saturn's in the last few times 10^8 years?

The fundamental questions confronting ring scientists at the beginning of the twenty-first century are those regarding the origin, age and evolution of the various ring systems, in the broadest context. Understanding the origin and age requires us to know the current ring properties, and to understand the dominant evolutionary processes and how they influence ring properties. Here we discuss a prioritized list of the key questions, the answers to which would provide the greatest improvement in our understanding of planetary rings. The answers to these questions may be different for each giant planet, since the rings and their environments are sufficiently dissimilar that they may not have common origins or ages.

Not surprisingly, many of our current key questions will be addressed either directly or indirectly by the Cassini mission. We have considered that mission in our deliberations and have attempted also to look beyond Cassini. Once Cassini data has been analyzed, priorities may change and unanticipated questions, missions and activities may need to be added to the lists below.

With the exception of two key questions raised in our discussions, the detailed questions which, if answered, will significantly improve our understanding of the origin and age of the rings can be grouped under a few prioritized broad tasks. Embedded within these tasks are key questions which will enable us to focus our search for better understanding of planetary rings. Based on a survey to which more than sixty percent of the participants responded, the key questions have been prioritized. The survey produced clear first and second choices (the question in section A and the first in section B below), followed by a large middle group of questions which were in turn rated as more important than the final two (the questions in sections E and F).

A. Characterize the physical properties of the various rings.

- What are the current physical properties (particle size distributions, particle shapes, the nature of particle aggregations, local kinematics, intrinsic strengths of particles and particle aggregations) of the various rings and of distinct regions within the rings?

B. Identify the most significant evolutionary mechanisms.

- What are the most important mechanisms for ring evolution on relatively long time scales?
- What are the most important mechanisms for evolution on relatively short time scales?

C. Determine the underlying kinematics and dynamics of the various ring systems.

- How fast are angular momentum and energy being transferred between rings and ringmoons?
- How do self gravity, viscosity, ballistic transport and collisions interact?

D. Determine the chemical compositions of the various ring systems.

- What is the current composition of the various rings and of distinct regions within the rings?

E. Characterize the mass flux into the various ring systems.

- What is the current mass flux into the various ring systems? What are the current size, mass, velocity, and composition distributions of the influx population? How did those distributions change with time?

F. Determine the influences of the magnetospheric and plasma environments of the various rings.

- What is the influence of the magnetosphere and plasma environment of the rings?

There were two additional questions, different in nature to the others, which were included in the survey and fall into the mid group of key questions. The first is a question we must continually ask as our understanding of individual ring systems improves. The other "different" question must be answered to enable us to better understand the data we gather from Earth-based activities.

G. What do the differences among ring systems tell us about differences in ring progenitors and/or differences in initial and subsequent processes?

H. What is the relationship between ring local properties and those properties observable via remote sensing?

We divide our recommendations into two broad categories: interplanetary spacecraft and activities that can be performed on or near Earth. In establishing priorities, we have produced ordered lists with the most important first. Within each list items tended to cluster naturally; consequently, the recommendations are divided into three groups: essential, critical, and important.

Among all of the possible activities that we considered for the decade, our overall number one priority is for robust support and augmentation of the Cassini nominal mission.

The current Cassini teams are excellent, but they are thinly staffed and funded. Most of the team members have been committing time far above the levels for which they have been funded. To capitalize on NASA's investment in Cassini, and to optimize the treasure house of data it will return, calls for an influx of new funding for the current teams, and for new blood to work alongside the current teams. At current funding levels it is not clear that the teams will have sufficient time to do the early data analysis required to refine the later mission sequences, not to mention to archive the incoming data in the PDS on the planned timescale. PDS archival is required before a long term data analysis program can be initiated, so the data archive pipeline must be fully functional before the wider community can become involved in Cassini data analysis. Early augmentation of the teams can ensure that both the teams' necessary internal data analysis, and prompt data archiving, can be accomplished in a timely way.

In the category of interplanetary space craft we recommned:

- ESSENTIAL. Increased funding for Cassini nominal mission: a participating scientist program (competitive, but probably limited selection), support for additional team associates (selected by teams), and a comprehensive data analysis program (competition open to the community). *Supports all key questions with respect to Saturn.*

- ESSENTIAL. Cassini extended mission (including associated support for data analysis and archiving). The initial extension should be for a minimum of approximately three years to encompass local observation of the next solar ring plane crossing and significant reopening of the rings. *Particularly important for key questions in sections A-D and the last additional question.*

- CRITICAL. Close-in orbiter to study Saturn ring microphysics at the level of individual particles, and the local ring environment in general. *Particularly important for key questions in sections A-C and F.*

- IMPORTANT. Neptune orbiter. *Supports all key questions with respect to Neptune.*

In the category of Earth-based or near-Earth activities, we recommend:

- ESSENTIAL. Long term observing campaign for the rings of Saturn. *Supports key questions in sections B-E.*
- CRITICAL. Simulations and laboratory experiments. *Supports all key questions.*
- CRITICAL. Periodic astrometric observations of Saturnian inner satellites. *Supports key questions in sections B, C and the last additional question.*
- CRITICAL. Develop a virtual theoretical laboratory to provide a vehicle for more coordination and integration of theoretical work. *Supports all key questions.*
- IMPORTANT. Long term observing campaign for the rings of Neptune. *Key questions in Sections B-D and the additional questions.*
- IMPORTANT. Long term observing campaign for the rings of Uranus. *Key questions in Sections B-D and the additional questions.*

REPORT

1. Current State of Knowledge

Galileo first recorded observations of the rings of Saturn in 1610. Subsequent observations produced more puzzlement than enlightenment as with time the features seemed to wax and wane. The fundamental question for seventeenth century scientists concerning these observations was "What are they?". The answer was provided in 1659 when Christian Huygens first demonstrated that the appearance was the result of a thin disk of material surrounding Saturn. The new fundamental question became "What is the structure of this disk, solid or many individual particles?". That question was not answered until 1859 when James Clerk Maxwell provided a mathematical proof that the rings could not be solid. The next fundamental question to be answered, which started to address the broader issues, was "Why is Saturn the only planet with rings"? This was drastically revised in the late 1970s and early 1980s with the discovery of the rings of Uranus, Jupiter, and Neptune, to "Why is Saturn the only planet with broad, bright rings?"

The discovery of the narrow, dark rings of Uranus (1977) was followed by the first Voyager images of the tenuous Jovian ring system (1979), and the spectacular data of many kinds returned during the twin Voyager flybys of Saturn (1980,1981). In subsequent years, ground-based stellar occultations, the Voyager flybys of Uranus (1986) and Neptune (1989), a handful of Galileo images, coupled with ground-based and HST observations continuing to the present, have defined planetary rings as a class of objects which broadened our perspective and stretched our theories to operate in different environments and regimes. The focus remains on the physics responsible for the phenomena we observe, as well as a newly compelling need to understand the origin and evolution of planetary rings in the general context.

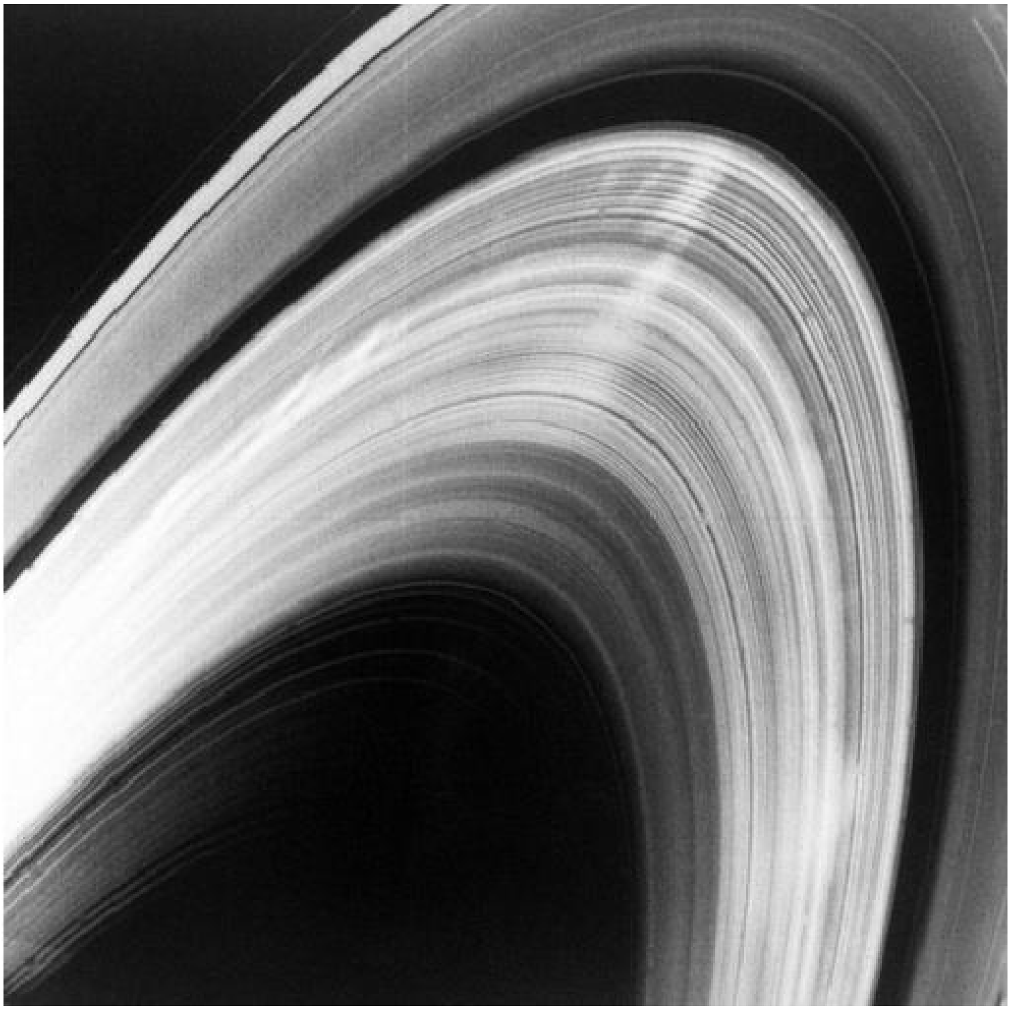

Figure 1. Voyager data like this Voyager 2 image of Saturn's rings, demonstrated that rings are far more spectacular and complex than our earlier theories predicted. This image shows Saturn's rings at high phase angle so that the radial spokes which are comprised of fine dust appear as bright patches above the complex and for the most part poorly understood structure of the B ring. Beyond the dark Cassini Division, the A ring too shows fine structure including the dark narrow band of the Enke gap. Unlike the structure in the B ring, most of the structure in the A ring is understood. Visible beyond the edge of the main rings is the enigmatic F ring, a narrow, multistrand ring which possesses a braided, kinked structure unlike any other known ring. (Image courtesy of NASA, and the Voyager mission).

Perhaps the greatest surprise was the complexity and variety of structure in the various ring systems revealed in the Voyager images. Recent studies have identified complex gravitational interactions between the rings and their retinues of attendant satellites. Among the four known ring systems, we see elegant examples of Lindblad and corotation resonances (first invoked in the context of galactic disks), electromagnetic resonances, spiral density waves and bending waves, narrow ringlets which exhibit internal modes due to collective instabilities, sharp-edged gaps maintained via tidal torques from embedded moonlets, and tenuous dust belts created by meteoroid impact onto, or collisions between, parent bodies. We are starting to realize that bombardment of rings by interplanetary meteoroids can have very significant effects on both ring structure and ring composition.

One glaring unresolved problem is the "record-groove" structure pervading Saturn's dense rings. This so-called "irregular structure" - so opaque that no light has ever been seen through parts of it - has scales from 10-300 km, is sometimes nonaxisymmetric, probably varies radially in particle packing density. In spite of a few hypotheses which have been advanced, its cause remains a mystery. Another major unsolved puzzle is Saturn's multi-stranded, clumpy F ring, which continues to defy a simple explanation more than twenty years after it was first glimpsed in grainy images taken by Pioneer 11. Voyager, HST and ground based active optics images reveal a complex, probably chaotic, dynamical interaction between unseen parent bodies within and perhaps surrounding this ring and its two shepherd satellites, Pandora and Prometheus. The orbits of the shepherds themselves seem to exhibit irregular jumps every few years.

The composition of planetary rings remains a major unknown, beyond some zero-order understanding. Infrared spectroscopy and microwave radiometry show that Saturn's rings are dominated by water ice; however, their pinkish color - not dissimilar from Triton at visual wavelengths - calls for at least one important secondary component. Different regions of the rings exhibit noticeable color variations on all scales, from local to regional, indicating compositional variation on all those scales. The color of the rings differs from the color of any of Saturn's icy moons. The composition of the rings of Jupiter, Uranus, and Neptune is unknown, but markedly different. The Uranian rings are nearly, but not entirely, colorless. The Jovian ring shares the reddish color of Amalthea, but the brightness of the particles is unknown because of the coupling with the unknown cross section of particles. The Neptunian rings are fairly dark, but nothing is known about their color.

The study of planetary ring dynamics has been instrumental in developing our understanding of the processes at work in the nebula during the formation of the solar system. In particular, the interactions between embedded objects and disks (spiral wave generation, angular momentum transport, truncation of disks) has been illuminated through our study of rings. Migration of bodies within an untruncated disk, due to angular momentum exchange with surrounding material, was first advanced in the ring context, and is now a mainstay of planetary formation models. The discovery and study of bending waves in the Saturn system was important in understanding how nebulae can be warped. Furthermore, our understanding of the development of chaos where resonances overlap has been elucidated through ring studies; certainly, similar studies of asteroid dynamics and the Uranian satellites also played a role here. Thus studies of planetary rings have been fundamental in improving our understanding of nebular dynamics and extrasolar planets.

As we have made progress in understanding the processes that influence planetary ring structure, there has been a growing realization that these processes can act to influence ring properties on timescales that are short compared to the age of the solar system. Global angular momentum transfer (torques) between Saturn's outer main rings and the inner ringmoons should be acting to expand the orbits of the moons, and to cause the rings to fall inwards accordingly. Bombardment of Saturn's rings by interplanetary projectiles should darken the ring particles to a charcoal-like appearance if the rings were as old as the solar system. Gas drag should remove the inner rings of Uranus on a short timescale as well. Transfer of tiny charged grains from Saturn's inner rings to the planet should deplete those rings on comparably short timescales. There are uncertainties in the parameters of all these processes, but they all go the same way and they all cause us to wonder about the origin of all four ring systems. Are they as old as the planets and their retinues of moons, or are they geologically recent and transient features of the planetary landscape?

Not surprisingly, many of our current key questions will be addressed either directly or indirectly by the Cassini mission. We have considered that mission in our deliberations and have attempted also to look beyond Cassini. We are at this time more than thirty months before Cassini's Saturn orbit insertion. Forecasting needs by first anticipating discoveries is an unsatisfactory process at best. Thirty months prior to Galileo orbit insertion, no one predicted that one of highest priority follow-on missions to Jupiter would be a Europa orbiter. The need for that mission only became apparent once the Galileo observations had been analyzed. Once Cassini data has been analyzed, priorities may change and unanticipated questions, missions and activities may need to be added to the lists below.

2. Key Science Questions

The fundamental questions confronting ring scientists at the beginning of the twenty-first century are those regarding the origin, age and evolution of the various ring systems, in the broadest context. Understanding the origin and age requires us to know the current ring properties, and to understand the dominant evolutionary processes and how they influence ring properties. Here we discuss a prioritized list of the key questions, the answers to which would provide the greatest improvement in our understanding of planetary rings. The answers to these questions may be different for each giant planet, since the rings and their environments are sufficiently dissimilar that they may not have common origins or ages.

With the exception of two key questions raised in our discussions, the detailed questions which, if answered, will significantly improve our understanding of the origin and age of the rings can be grouped under a few prioritized broad tasks. Embedded within these tasks are key questions which will enable us to focus our search for better understanding of planetary rings. Based on a survey to which more than sixty percent of the participants responded, the key questions have been prioritized. The survey produced clear first and second choices (the question in section A and the first in section B below), followed by a large middle group of questions which were in turn rated as more important than the final two (the questions in sections E and F).

A. Characterize the physical properties of the various rings.

What are the current physical properties of the various rings and of distinct regions within the rings?

In order to determine the origins and ages of the various rings, we must first establish the current state of the rings with far greater certainty than is currently possible. We need to know the particle size distributions of the various regions within the rings. In order to interpret remote observations, we need to know the particle shapes and the nature of particle aggregations. In order to refine models of local dynamics, we need to know more about the local kinematics down to the level of establishing the local value for the coefficient of restitution, as well as the intrinsic strengths of both the particles and particle aggregations. For dusty rings, particle size is a key parameter defining how the grains respond to non-gravitational forces, including electromagnetic perturbations and solar radiation pressure. The size also determines particle lifetimes against sputtering and micrometeoroid erosion. Finally, each dusty ring requires an embedded population of larger source bodies. These populations are rarely seen but they play a critical role in defining the origin and evolution of dusty rings.

B. Identify the most significant evolutionary mechanisms.

What are the most important mechanisms for ring evolution on relatively long time scales?

While we have a fairly good idea that the main mechanisms are related to gravity, viscosity, and bombardment, the statement of this key question is misleadingly simple. Planetary rings are far from the relatively homogenous and static distributions of particles envisioned prior to the revelations of the Voyager spacecraft. The complex macro-structures, rings, ringlets, gaps, and waves vary with time. The composition of a ring changes as material is lost from the ring and replenished by new material from a variety of sources; individual particles change size and other characteristics due to a variety of processes. Different mechanisms will be more important in different regions and for different particle distributions. Since the regions are not static, the set of most important evolutionary mechanisms will itself evolve.

What are the most important mechanisms for evolution on relatively short time scales?

Saturn's F ring, and its surrounding regions, show clumps which come and go on timescales of days to weeks. There are several alternate hypotheses which explain this by a combination of external impacts and collisions between embedded moonlets too small to see directly. Is there a belt of as-yet unseen moonlets undergoing collisional evolution? Is the F ring itself a recent member of the system? The shepherds themselves undergo sporadic orbital jumps. Is dynamical chaos, produced by overlapping resonances in this tightly coupled region, responsible? Or, are there massive bodies buried within the F ring which perturb the orbits of these objects? The enigmatic spokes in Saturn's B ring form and disperse in half of a ring revolution. If meteoroid bombardment onto the rings is the trigger, can the current observed frequency of meteoroid impacts explain the frequency of the spokes? Are the Neptune ring arcs indeed confined in corotational resonances, or are they themselves transient? While gravity and collisions are likely to dominate in relatively massive rings, dusty rings have a rather different set of evolution mechanisms, including electric charging, electromagnetic forces, solar radiation pressure, and sputtering.

C. Determine the underlying kinematics and dynamics of the various ring systems.

How fast are angular momentum and energy being transferred between rings and ringmoons?

Two decades ago it was realized that current theories, now well supported by detailed analysis of spiral density waves and bending waves, predict that the orbits of Saturn's inner ringmoons should be expanding at a rate that could be observed by comparing Cassini and Voyager observations. This would allow the "age" of the rings to be determined. It has now been revealed by HST observations that these orbits display even larger, more sporadic, fluctuations. This greatly complicates the problem of unraveling the mean global rate of momentum transfer. Nevertheless, the problem is a central one and more sophisticated approaches of solving it must be sought.

How do self gravity, viscosity, ballistic transport and collisions interact?

Viscosity and gravity compete to form "overstabilities" - stable, nonaxisymmetric structures which are still poorly understood. Both viscosity and local self gravity probably play a role in forming "wakes" which trail embedded moonlets, but only one of these wakes has as yet been studied in the Voyager data. Viscosity depends on particle random velocities, and local "particles" influence particle random velocities. Because "particles" might be transient, gravitationally formed clumps themselves, the aspects of transport usually lumped into "viscosity" may have to be handled somewhat differently for different applications or different particle sizes. Although the time scale for ballistic transport is longer than collision or orbital time scales, its ability to produce ring structure is strongly influenced by these other transport mechanisms.

D. Determine the chemical compositions of the various ring systems.

What is the current composition of the various rings and of distinct regions within the rings?

In order to determine the origins and ages of the various rings, we need to know the chemical composition of the ring particles. Different material might be left over from ring formation, deposited from outside the system, or possibly modified in place. The spatial distribution of material of different composition will allow these possibilities to be separated.

E. Characterize the mass flux into the various ring systems.

What is the current mass flux into the various ring systems? What are the current size, mass, velocity, and composition distributions of the influx population?

New material is constantly being added to the rings as the result of meteoroid bombardment, and this mass flux is one of the mechanisms for ring evolution. The compositional and structural effects of this bombardment can provide constraints on ring age independent from angular momentum arguments. However, those effects remain undetermined because of the poorly known interplanetary mass flux in the outer solar system. Ideally, for each of the ring systems, it would be best to know the combined size, mass, velocity and composition distributions of incoming material as a function of ring radius and ring longitude. To fully constrain ballistic transport (the evolution of ejecta from impacts), we need the equivalent of a mass intensity for the projectiles (he mass flux of small projectiles into the rings as a funtion of both ring radius and direction). The direction matters because the relative amount of impacts on the forward and trailing ring particle hemispheres matters. We need to know mass and velocity separately because the ratio of impact ejecta mass to projectile mass depends on the impact speed.

F. Determine the influences of the magnetospheric and plasma environments of the various rings.

What is the influence of the magnetosphere and plasma environment of the rings?

The faint, dusty rings of Jupiter and Saturn illustrate a number of the possible links between ring dust and the planet's magnetosphere and plasma environment. The three dimensional structure of Jupiter's inner halo is defined by orbital resonances with the planet's rotating magnetic field. The structure of Saturn's broad E Ring is probably defined by a particular match between electromagnetic forces, solar radiation pressure and Saturn's gravity field, which enables some dust particles to be dispersed widely throughout the Saturn system. Unfortunately, the electric charge on grains, which is so critical to defining their motion, depends on properties of the plasma environment that are very poorly known. The "spokes" which flicker across the face of Saturn's rings might be triggered by meteoroid impacts or by electromagnetic instabilities. Their propagation and occurrence display unmistakable signatures of the planet's magnetic field, including connections to its longitudinal asymmetry. Orbital instabilities of tiny charged grains might be a significant loss mechanism of ring material to the planet. The properties of the local plasma and charging environment at the ring plane are unknown, and yet are critical to advancing our understanding of these important phenomena.

There were two additional questions, different in nature to the others, which were included in the survey and fall into the mid group of key questions. The first is a question we must continually ask as our understanding of individual ring systems improves. The other "different" question must be answered to enable us to better understand the data we gather from Earth-based activities.

G. What do the differences among ring systems tell us about differences in ring progenitors and/or differences in initial and subsequent processes?

   Much of our understanding of the geologic and atmospheric activities of the planets comes from comparative planetology. So too with planetary rings, comparisons between the various ring systems will provide insights beyond those achievable by viewing each ring system in isolation. This key question will be asked repeatedly as our understanding of individual ring systems improves.

H. What is the relationship between ring local properties and those properties observable via remote sensing?

   Much of our current knowledge is based on modeling local ring properties theoretically, predicting remotely observed properties from these models, and adjusting the various models to achieve the closest match to observations. We need to validate our understanding of the parameters within those models. Planetary scientists have gained insights into the geology of Mars by interpreting Martian observations within the knowledge context of Terrestrial field geology. Geologists have walked the shores and deserts, climbed the mountains, descended into the canyons of Earth, have studied the rocks of Earth in the field and in the laboratory, all of which establishes a foundation for remote studies of distant bodies. No one has yet been to a ring.

3. Recommendations

We divide our recommendations into two broad categories: interplanetary spacecraft and activities that can be performed on or near Earth. In establishing priorities, we have produced ordered lists with the most important first. Within each list items tended to cluster naturally; consequently, the recommendations are divided into three groups: essential, critical, and important.

Among all of the possible activities that we considered for the decade, our overall number one priority is for robust support and augmentation of the Cassini nominal mission.

In the area of interplanetary spacecraft, our recommendations are as follows:

- ESSENTIAL. Increased funding for Cassini nominal mission: support for a participating scientist program (competitive but probably limited selection), additional team associates (selected by team members) and a comprehensive data analysis program (competition open to the community).

  Cassini has a powerful array of instruments either new or improved, and a scheduled four year tour with numerous observing geometries. It's hard even to imagine the new things we'll discover and the new questions which will emerge as we get tens of thousands of images in many filters and several polarizations, hundreds of detailed UV and IR spectra at resolutions adequate to resolve most of the ring structure, approximately a hundred stellar and radio occultations, thermal emission in infrared and microwave spectral regions, and in-situ measurements of dust, gas, and plasma abundance and composition around the rings (and even right above them during Saturn Orbit Insertion). Cassini is NASA's single largest investment in planetary science.

  The current Cassini teams are excellent but they are thinly staffed and funded. Most of the team members have been committing time far above the levels for which they have been funded. To capitalize on NASA's investment in Cassini, and to optimize the treasure house of data it will return, calls for an influx of new funding for the current teams, and for new blood to work alongside the current teams.

  At current funding levels it is not clear that the teams will have sufficient time to do the early data analysis required to refine the later mission sequences, nor to archive the incoming data as rapidly as planned. Data archiving is the necessary intermediate step between data acquisition and data distribution to the community at large. The planned data archive pipeline must be fully functional before the wider community can become involved in Cassini data analysis.

  Early augmentation of the current teams can ensure the staffing for the teams' necessary internal planning, data analysis and publication, as well as prompt data archiving for the benefit of the broader community. Broader community involvement can be achieved through the implementation of a sustained data analysis program beginning approximately one year after Saturn Orbit insertion and continuing several years beyond the end of the mission.

- ESSENTIAL. Cassini extended mission (including associated support for data analysis and archiving). The initial extension should be for a minimum of three years to encompass local observation of the next solar ring plane crossing and subsequent significant reopening of the rings.

  Cassini's nominal tour ends in July 2008, well within the period covered by this decadal study. Hopefully, it will be in good health and have ample propulsion reserve to go several years longer. Based on the earliest look at science planning for the nominal four year tour, there will not be enough time or data volume to do any more than a "must have" subset of all the ring observations one could imagine doing. From the standpoint of addressing any of the more detailed level "key questions" we can identify now, we can't think of a single higher priority approach we could recommend than the full-up continuation of Cassini into an extended mission, bolstered by a budget line built right into NASA's planning wedge which would include robust participating scientist opportunities, continuation of the data analysis program and maintenance of the data archiving pipeline to allow that flood of data to be preserved, disseminated, analyzed and interpreted.

During such an extended mission, the rings will close up as seen from Earth, and then reopen again. This provides new opportunities for radio occultations to pick up great sensitivity in the optically thin regions. Close up observation of the rings with edge on illumination will allow high resolution studies of vertical corrugations and provide an opportunity to observe the illuminated side of the rings at high phase angles (not possible in Earth based observations). Spokes might become visible again for the first time in the mission (spokes have never been seen when the Sun/Earth elevation angle is larger than about 4-5 degrees). All instruments will continue to monitor the rings for changes, zoom in on interesting features, improve spectral resolution and coverage, and refine radial resolution and longitudinal coverage in new illumination and viewing geometries. Such an extension will provide the longer time needed to observe the several dynamical phenomena which are known to operate on 5-10 year timescales in the main rings and in the F ring. Perhaps most important of all will be the opportunity to follow up on the inevitable new discoveries with dedicated, multi-instrument campaigns, to distinguish between the competing hypotheses which will quickly arise.

- CRITICAL. Close-in orbiter to study Saturn ring microphysics at the level of individual particles, and the local ring environment.

Despite everything Cassini will accomplish, we will not learn much directly about ring microphysics, physics at the level of individual particles. Currently we infer such processes indirectly from remote sensing data, but those inferences have never been truly validated by detailed in-situ observations. In the main rings, we are dealing with a self-gravitating, collisional, particulate system inside its planet's Roche zone with disparate particle sizes, a wide range of densities, random velocities and packing densities, subject to a variety of influences. Even subtle influences can have important effects over time. We need direct information about the microphysics.

Second, minor constituents of the ring material, or complex organic molecules, might never be detectable in remote observations, even by Cassini. Certainly, isotopic compositions and the presence or absence of noble gases will never be detectable remotely. All of these contain important clues to ring origin.

Third, the effort to understand fully several important processes requires us to know what the local environment of the ring particles is. What is the electron density in the surrounding plasma, and how is it maintained? What is the charge on small dust grains and what are their motions? What sort of impact plasma or cloud forms when a meteoroid slams into the rings at 70 km/second, and how does it evolve? Are there electromagnetic instabilities? Can material from the planet's ionosphere modify ring particle properties?

Some of these questions might be addressed by a focused, relatively short term mission perhaps in the Discovery class. The spacecraft would operate just out of the ring plane, "hovering" above various regions within Saturn's main rings. It would need the capability of altering its radial distance from the planet in order to sample different regimes. This mission, depending on instrument packages and mobility, could address six to eight of the key questions at levels of detail that cannot be achieved by Cassini. Such a mission might be a suitable test bed for an ion drive engine.

The mission needs to arrive at Saturn near the time when the rings are the most open to the sun - both for optimum illumination, and for easy insertion into equatorial orbit. The next opportunity for such a mission would be with arrival in the interval between 2014 and 2016. The subsequent window would be approximately fifteen years later.

- IMPORTANT. Neptune orbiter.

The next most interesting ring system after Saturn, is probably that of Neptune. It has the additional scientific interest of being the most remote in the solar system, and the closest to the Kuiper Belt. There is a massive inner ringmoon belt with probably many smaller moons Voyager couldn't find. There are diffuse dusty rings. This is the only ring system known to possess relatively stable arcs, although the proposed confinement mechanism has recently come into question as a result of recent HST observations of the clumps. The vertical and radial structure of the Neptunian rings remain unresolved; we are completely ignorant of the ring and ringmoon composition or how it varies with location, except that the material seems to be dark. We are likely always to remain ignorant if we have to rely on Earth-based observations alone. Are the ring arcs indeed trapped or are they evolving? Are they "rubble belts" containing large boulders as well as dust? Are they the results of disruption of moons? How long ago? What is the meteoritic in fall rate and composition? Voyager data contains hints of other narrow, kinky ringlets in a few as-yet unstudied images.

New ground-based observations may provide more insights, but ground-based observations of the Neptunian rings have serious limitations. It is best to view dusty rings in forward-scattered light, which places the rings between the observer and the Sun. This requires spacecraft.

If more new answers and discoveries come from lifting the veil on areas where our ignorance is the deepest, the Neptunian system clearly offers the greatest potential for expanding our knowledge. Bringing our understanding of the Neptunian rings up to a similar level as the Saturnian and

Jovian rings would greatly enhance the ability of the rings community to do real comparative studies. We would be better able to address the key question "Why are the ring systems of the giant planets so different?" which necessarily requires that we get one or two of the outer most ring systems up to a level of understanding approaching the Saturn ring system (Voyager-Saturn level, if not Cassini-level).

In the area of Earth-based or near-Earth activities, we recommend:

- ESSENTIAL. Long term observing campaign for the rings of Saturn.
- CRITICAL. Simulations and laboratory experiments.
- CRITICAL. Periodic astrometric observations of Saturnian inner satellites.
- CRITICAL. Develop a virtual theoretical laboratory to provide a vehicle for more coordination and integration of theoretical work.

  We need to consider more coordinated theoretical efforts than are currently the norm. We have begun to develop "virtual observatories". A similar effort has proven beneficial in the study of stellar structure. Some coordination of theoretical efforts does occur in ring science, but not in a coherent and consistent fashion. Now is the time to develop a virtual theoretical laboratory to facilitate better coordination and more systematic integration of those efforts.

  Useful facilities can be envisioned at very different levels of sophistication. Goals could range from modest ones, such as coordinating activities among various ring theory groups, to ambitious ones, such as providing and maintaining easy-to-use, robust, rigorously tested on-line modular software laboratories which permit users to undertake complex simulations and to visualize their results without undo concern about where or how the computations are being done. In the latter case, the "laboratory" must be funded well enough that requisite computational and software facilities can be developed, maintained, and documented by teams of planetary scientists, computational scientists, software analysts, and system managers and technicians. The lab would be "virtual" in that the teams responsible for different software areas and the computational facilities utilized by the laboratory could have a wide geographical distribution. Although the concept originated in our Ring Panel discussions as a way to help provide more focus and cooperation among ring theorists, there is no reason to limit its scope to rings over the coming decade. It may perhaps be time to work toward establishment of a national if not global virtual laboratory for astrophysics and planetary science. The larger facility could evolve from virtual laboratories designed for specific problems deemed of central importance to various disciplines.

- IMPORTANT. Long term observing campaign for the rings of Neptune.
- IMPORTANT. Long term observing campaign for the rings of Uranus.

Uranian ring plane crossings occur approximately every forty-two years. The next such ring plane crossing will be in 2007. Thus during the decade of this study we will be afforded a rare opportunity to observe the edge-on rings. In order to maximize the return from this viewing opportunity we need to establish a high resolution viewing campaign that extends throughout the decade in order to encompass the entire cycle as the ring opening angle closes and then reopens to a significant amount.

4. Data Archive and Access Issues

Some processes within planetary rings operate on sufficiently short timescales to permit the detection of changes on timescales ranging from days to decades or tens of decades. In order to gain insights into the underlying processes, it must be possible to access and analyze historical data. Spacecraft data associated with planetary rings studies are archived and distributed by the NASA Planetary Data System. A limited amount of Earth based and HST data have also been archived. The volume of planetary data will increase dramatically during the coming decade. The PDS should expand its capability to provide online distribution of data sets, provide tools for fine grained searches of the data, and tools to return basic observational parameters. Efforts to incorporate Earth based data should continue and tools to simplify the submission of data to the PDS be developed.

5. Education and Public Outreach

Planetary rings are among the most spectacular and appealing objects in the solar system and possess the capability to capture the imagination of young people. Various aspects of rings studies can be organized to allow high school and undergraduate students to actively participate in the search for better understanding. Properly organized such efforts should leave them with a sense of the search for understanding rather than the all too frequent classroom approach that encapsulates the proposed question with the neatly presented correct answer.

6. Summary

The decade covered by this White Paper is critical to our quest to understand the age, origin and evolution of planetary rings. The Cassini spacecraft arrives at Saturn in the second year of the study decade for a nominal mission of four years and the potential to continue operations throughout the bulk of the decade. The unique viewing geometry and illumination of the rings associated with solar ring plane crossings for Saturn (every fifteen years) and Uranus (every forty two years) both occur during this decade.

The Cassini mission provides the cornerstone and focus for efforts to better understand the composition and processes of Saturn's rings, and must be done right. Cassini has received significant funding drawbacks from HQ over the last few years and the science teams are stretched extremely thin. To capitalize on

NASA's investment in Cassini, and to optimize the treasure house of data it will return, we call for an influx of new funding for the current teams, for new blood to work alongside the current teams, and for a comprehensive Cassini Data Analysis program to be established.

Beyond the Cassini nominal mission should be more Cassini. Even before Cassini arrives in orbit at Saturn, it is clear that if the spacecraft remains healthy, a Cassini extended mission will provide the best science for dollar return in the outer solar system. Such a mission extension should be anticipated and fully funded.

Following Cassini a dedicated mission to study the detailed interactions of Saturn's main rings at the individual ring particle level should be undertaken.

Throughout the decade comprehensive, systematic observation programs need to be supported for the all of the planetary ring systems. Theoretical work will be greatly enhanced by influx of new data. New approaches to the coordination and sharing of that work need to be explored taking advantage of the potential inherent in the high speed, reliable connectivity possible with advances in modern computing.

References

There is a wealth of information available in the literature. We give here a few of the review papers written in recent years that relate to the study of planetary rings. These papers and the references contained within them will provide the interested reader a detailed look at the past, present, and future focus of planetary ring science.

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