

Rings Research in the Next Decade

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I. Executive Summary

The study of planetary ring systems forms a key component of planetary science for several reasons: 1) The evolution and current states of planets and their satellites are affected in many ways by rings, while 2) conversely, properties of planets and moons and other solar system populations are revealed by their effects on rings; 3) highly structured and apparently delicate ring systems may be bellwethers, constraining various theories of the origin and evolution of their entire planetary system; and finally, 4) planetary rings provide an easily observable analogue to other astrophysical disk systems, enabling real “ground truth” results applicable to disks much more remote in space and/or time, including proto-planetary disks, circum-stellar disks, and even galaxies.

Significant advances have been made in rings science in the past decade. The highest priority rings research recommendations of the last Planetary Science Decadal Survey (Belton *et al.* 2003) were to operate and extend the Cassini orbiter mission at Saturn; this has been done with tremendous success, accounting for much of the progress made on key science questions, as described in more detail below. Important progress in understanding the rings of Saturn and other planets has also come from Earth-based observational and theoretical work, again as prioritized by the last Decadal Survey (see also Gordon *et al.* 2002).

However, much important work remains to be done. At Saturn, the Cassini Solstice Mission must be brought to a successful completion. Priority should also be placed on sending spacecraft to Neptune and/or Uranus, now unvisited for more than 20 years. At Jupiter and Pluto, opportunities afforded by visiting spacecraft capable of studying rings should be exploited. On Earth, the need for continued research and analysis remains strong, including in-depth analysis of rings data already obtained, numerical and theoretical modeling work, laboratory analysis of materials and processes analogous to those found in the outer solar system, and continued Earth-based observations.

II. Key Science Questions

The priorities described in this document reflect the results of a survey of professional rings scientists. Over thirty invitees (including many of the listed co-authors of this document) participated in the survey, representing a broad spectrum of the sub-fields of rings science. Respondents rated the importance of eight Key Science Questions and eleven Specific Action Recommendations on a scale ranging as follows: Essential, Priority, Important, Less Important, and Not Important. The Key Science Questions were based on those in the survey conducted by Gordon *et al.* (2002) in support of the last Planetary Science Decadal Survey, but the priorities listed here reflect the impact of the past decade’s progress.

Of the eight science questions ranked in our survey, the top four were given nearly equal value:

1. What are the current physical structure and dynamics of the various rings and distinct regions within the rings?

Cassini data, supported by numerical and theoretical models, have revealed a wealth of dynamical structures in Saturn’s rings that require further investigation, including textures in the main rings produced by inter-particle interactions and patterns generated by perturbations from distant and embedded satellites.

Collective inter-particle interactions produce phenomena including “self-gravity wakes” formed by a constant process of clumping counter-balanced by tidal shearing; concentric

oscillations in the denser parts of the rings that may be due to viscous over-stability; and the “straw” like textures in regions of intense collisional packing such as strong density waves and ring edges. Some of the still-unexplained large-scale radial structure in the B and C rings might also be explained by inter-particle interactions. These features provide essential clues as to how these rings and other disks of material behave.

Disk-moon interactions are critical for rings, as well as other astrophysical disks. Spiral density waves and bending waves, raised by orbital resonances with distant moons, can provide useful information about local ring properties, though the nonlinear behavior of the strongest waves has yet to be fully quantified and the origins of several waves have yet to be determined. In other situations, resonances with moons produce longitudinally confined arcs in Saturn’s dusty rings, enabling comparisons with arcs in the Jovian and Neptunian rings whose origins are more obscure. Moons embedded within the rings are observed to produce gaps, though the mechanisms behind many gaps remain unknown. Sharp gap edges display an unexpected array of fine azimuthal structure. Smaller embedded objects are likely responsible for newly revealed “propeller” structures in the A ring and various features in the F-ring core; these phenomena hold the promise of direct detailed study of the interaction and evolution of disk-embedded masses.

For the Jovian, Uranian and Neptunian rings, further work is needed to characterize azimuthal structures observed in the ring edges, search for as-yet undiscovered shepherd and/or source moons, determine the mechanisms responsible for confining various arcs, and explore the possible role of inter-particle effects like self-gravity wakes.

2. What are the most important mechanisms for evolution on long timescales?

New Cassini results have focused much attention on the origin and age of Saturn’s rings. The realization that the B ring may be much more massive than previously thought has the potential to ease a primary constraint on the rings’ age, namely pollution by interplanetary mass infall, and may also make less likely a ring origin more recent than the Late Heavy Bombardment. However, long-term tidal evolution and particle erosion remain issues to be resolved for the hypothesis of many-Gyr-old rings.

Similarly, fundamental questions regarding the long-term stability of the Uranian and Neptunian rings remain to be addressed. Can their highly structured form be maintained for many Gyr? Do their dark surfaces require many Gyr to form?

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

Nearly all constituent ring particles are too small to observe individually, so proper interpretation of observations requires understanding their collective effects and behavior. Thus, for example, theoretical and numerical analyses of ring dynamics are essential to interpreting the photometry of Saturn’s rings as observed by Cassini and from Earth-based telescopes, and laboratory testing of ring-forming materials are needed to understand ring spectroscopy.

4. What are the current chemical and physical properties of the individual objects/particles making up the various rings and distinct regions within the rings?

Data from Cassini’s spectrometers and other instruments are shedding light on the composition and thermal properties of particles in Saturn’s rings, as well as the

characteristics of regolith on larger ring particles. These properties are now seen to vary over different regions of the rings, for reasons that need to be better understood.

The chemical and physical properties of Uranian and Neptunian ring particles are almost completely unknown. It is highly desirable to characterize them for comparative study.

The second set of four science questions in our survey were ranked in a clear order of descending priority:

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

Why is Saturn alone surrounded by a massive dense disk? Why does only Neptune have arcs in its dense rings? Why is Jupiter the only planet without dense rings of any kind? What can these differences teach us about differing origins, histories, or current states of these planetary systems?

New views of Saturn's rings from Cassini have led to new ideas about their age and origins. It is now even more desirable to bring our knowledge of other planetary ring systems up to a level where meaningful comparative studies can be undertaken.

6. What are the most important mechanisms for evolution on measurably short timescales?

Cassini has revealed that significant structural changes in Saturn's D and F rings have occurred on decadal and shorter timescales. Ground-based monitoring has detected similarly fast changes in the rings of Neptune and possibly Uranus. The mechanisms behind these changes remain mysterious, and it is highly desirable to see these changing structures in greater detail and to monitor them for future change.

The direct detection of orbital migration remains a major goal for Cassini, either for moons interacting with the rings (see above) or for embedded "propeller" moonlets, reflecting processes in proto-planetary disks.

Dusty rings are continuously generated by the ejection of debris from source moons, so the evolutionary timescales of individual constituent particles are generally short compared to the age of the entire system.

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

Angular momentum is transferred via spiral density waves from Saturn's rings to more distant perturbing moons. Over long times, the moons' orbits should evolve outward while the rings evolve inward, potentially placing a limit on the age of the rings that has previously been estimated to be as small as a few hundred Myr. Cassini is closely monitoring the moons' orbits so as to directly detect this transfer of angular momentum.

8. How do rings interact with their environment, including magnetosphere, plasma, and interplanetary mass flux?

The infall of interplanetary mass onto Saturn's rings may constrain its age, and a major continuing goal of Cassini is to measure that flux. Non-gravitational forces, including electromagnetism, drive the evolution of dusty rings such as Saturn's E ring and Jupiter's Gossamer rings, but much work is still needed to clarify the processes involved.

For further detail on all the advances described above, we refer the reader to the upcoming book *Saturn from Cassini-Huygens* (Dougherty *et al.* 2009), especially chapters 13 through 17, which summarize recent advances in Saturn rings science. Also, the textbook by Miner *et al.* (2007) reviews all planetary ring systems, including recent advances at Jupiter, Uranus, and Neptune.

III. Specific Action Recommendations: Space Missions

In the category of space missions, our survey results showed one recommendation that was a clear consensus favorite over all the others, three more that were strong priorities, and a final two that were also ranked as important.

A. ESSENTIAL: Rings science at Saturn by the Cassini Solstice Mission orbiter

The Cassini Prime Mission and Cassini Equinox Mission have revolutionized our understanding of Saturn's rings (see Section II). The Cassini Solstice Mission (CSM) takes advantage of the highly capable flagship spacecraft already in place at Saturn to investigate seasonal and temporal changes in the rings throughout the northern summer (2009-2016), and furthermore to investigate new questions that have only come to light during the initial Cassini Missions. The mission will culminate in a series of spectacular high-inclination orbits diving into the ring region, ending with an impact into Saturn's atmosphere (Dougherty *et al.* 2009, chapter 22).

Priority rings science in the CSM includes a) intensified study of gaps and gap edges in an effort to discover the moons (or other mechanisms) responsible for their radial confinement; b) monitoring the thermal response of ring material as northern spring turns into summer; c) high-spatial-resolution compositional measurements of selected areas; d) continued surveillance of the fast-evolving structure of the F ring; e) tracking the orbits of "propeller-moonlets" embedded in the A ring so as to detect or constrain their orbital migration; and f) an attempt to directly measure the rings' mass using Doppler gravity data during the final set of close-in orbits.

It is essential to the progress of rings science that the Cassini Solstice Mission be fully funded and aggressively supported.

B. PRIORITY: Rings science at Neptune by a future orbiter or flyby

C. PRIORITY: Rings science at Uranus by a future orbiter or flyby

In the two decades since Voyager 2 flybys, the relevance and urgency of a space mission to the rings of one of the ice giants with modern instrumentation has grown considerably.

The most remarkable features of Neptune's rings are the azimuthally confined arcs embedded in the Adams ring. Although a resonance mechanism has been proposed for the confinement of these arcs, post-Voyager observations have cast at least the details into doubt; the same observations also reveal that the arcs are evolving on timescales as short as decades, consistent with our emerging perspective of rings as dynamically evolving and changing on human timescales. Further close-range observations of both the rings and the associated moons will likely contribute a great deal towards resolving the outstanding questions regarding their nature and persistence.

The Uranian ring system is massive, complex, and diverse, and much about it remains poorly understood. It includes several narrow and sharp-edged dense rings whose confinement mechanism is yet unclear. New components of the Uranian ring system,

discovered from post-Voyager Earth-based observations, have yet to be characterized at close range. Over the next two decades, the rings will go from nearly edge-on to the Sun to fully open to the Sun (equinox 2007, solstice 2028). The temporal effects of Uranus' extreme seasons on the rings are unknown but possibly considerable.

Both ring systems demonstrate temporal changes detectable in Earth-based observations, although those observations are inadequate to identify the causes. The composition and particle-size distribution of the ring systems of the ice giants are almost completely unknown, though it appears the particles are very dark. Observing the rings at close range in the infrared, which has never been done, would considerably enhance our understanding of their origin and evolution, as would observations at high phase angles that are inaccessible from Earth.

We strongly urge the selection of a Neptune or Uranus mission including a robust rings science component. Either an orbiter or a flyby would significantly enhance our current understanding of these systems. An ideal rings science package would include a sensitive imaging camera, near-infrared spectrometer, and radio and/or stellar occultations. Recognizing that it is not likely that missions to both will be selected in the next decade, we emphasize that our survey of rings scientists found strong support for both of the ice giant planets as high-priority targets for rings science, with a slight preference for Neptune over Uranus.

D. PRIORITY: Rings science at Saturn by a post-Cassini orbiter or flyby

Any future mission to Saturn, including one focused primarily on Titan and/or Enceladus, as well as any mission that flies past Saturn on its way to a more distant target, must make it a priority to investigate Saturn's rings as opportunities allow. It is desirable to know how the rings will have continued to evolve after the end of the Cassini mission, and furthermore it is likely that an orbit-insertion or gravity-assist maneuver will make possible some highly favorable viewing geometries on the rings.

Even more desirable would be a dedicated Saturn Rings Observer (SRO), which can potentially obtain rings data with unprecedented spatial resolution and temporal coverage. Basic mission concepts might include:

- a “hoverer” that uses periodic or continuous low-level vertical thrust to maintain a trajectory within the ring region while avoiding the ring plane,
- a conventional orbiter that remains in circular orbit just outside the F ring, and/or
- micro-probes that embed themselves within or among particles in the dense rings.

Initial engineering studies for each of these ideas exist – see Spilker (2003) for a “hoverer,” and Marty *et al.* (2009, sections 3.4.3 and 4.8) for micro-probes. However, further work is required to develop a robust mission concept, and missions to Neptune and Uranus currently represent higher priorities.

E. IMPORTANT: Rings science at Jupiter by the Juno, EJSM, and/or other future orbiter or flyby

The recent New Horizons flyby has demonstrated the value of continued observations of Jupiter's rings, revealing new structure that still needs to be fully understood. Future missions to Jupiter – including the selected Juno mission, the planned EJSM orbiter, and any other mission encountering Jupiter en route to another target – should make it a priority to observe Jupiter's rings as opportunities allow.

F. IMPORTANT: Rings science at Pluto by the New Horizons flyby

Pluto does not have a known ring system, though studies have discussed the dynamical and observational likelihood of tenuous dusty rings. The planned New Horizons flyby should contain appropriate observations to search for and characterize Pluto's rings.

IV. Specific Action Recommendations: Earth-based Activities

In the category of Earth-based activities, our survey found four priority recommendations, ranked in a clear descending order.

G. PRIORITY: Continuing analysis of data already obtained by Cassini and other missions through programs including CDAP, PG&G, and OPR

A robust program of research and analysis (R&A) funding is an essential support component for space missions. Mission science teams generally are not funded to carry out in-depth analysis, so mission scientists must find non-mission funding for such work. Additionally, R&A funding allows members of the science community from outside a mission's science team to contribute to the science return of that mission.

In particular, the services of the Planetary Data System (PDS) are essential for in-depth analysis of data from all space missions, and the Cassini Data Analysis Program (CDAP) specifically funds in-depth analysis of Cassini data. Funding for both must be sharply increased so that we may fully receive the promised return in science results on previous investment of money and effort into the Cassini mission.

We urge continued strong support for mission-related R&A funding.

H. PRIORITY: Numerical simulations and other theoretical investigations of ring dynamics

Even the highest-resolution rings observations obtained to date are at spatial scales at least two orders of magnitude larger than the size of nearly all individual ring particles, and furthermore the temporal coverage at high resolution is poor. Therefore, numerical simulations and other theoretical models underlie our current understanding of many ring processes. Advances in available computing power have resulted in much progress in this area. In particular, collective effects within dense rings, such as self-gravity wakes and viscous over-stability, are currently understood primarily from numerical simulations of micro-structure that predict and explain larger-scale observables.

I. PRIORITY: Develop new technologies to enable more robust future missions to outer planet systems

Effectively exploring the outer solar system, in many ways, stretches our technical capabilities. Yet the considerable rewards make it worthwhile to invest in technologies that will enable more outer solar system missions to be undertaken in a cost-effective manner, particularly power supplies and propulsion systems as well as improved instrumentation. We encourage the engineering community to think creatively of new ways to accomplish the science goals enumerated in this document, and we encourage the appropriate allotment of funds to develop such new technologies.

J. PRIORITY: Laboratory experiments to investigate chemical and physical properties of materials constituting ring particles

The inference of ring material properties from spectroscopic observations relies on “ground truth” laboratory measurements of the spectroscopic properties of various ices. Much work remains to be done in making laboratory ices more realistic representations of actual materials in the outer solar system, including carrying out experiments under appropriate temperature and pressure conditions.

Similarly, values of certain physical parameters such as the coefficient of restitution, so essential for numerical simulations and theoretical models, rely on direct laboratory measurements. We must continue to conduct such experiments and improve their realism.

Finally, we present one more high-priority recommendation that we do not quantitatively compare to those listed above:

K. PRIORITY: Earth-based observations of the rings and satellites of the giant planets

Some planetary ring systems are not currently monitored by spacecraft, making it necessary to monitor these systems from Earth. In recent years, such observation campaigns have paid particularly high dividends in the discovery of new components and/or temporal change in the rings of Uranus and Neptune.

Additionally, certain important kinds of observations can only be performed from Earth, including large-scale photometry and RADAR studies, observations at very low phase angle, monitoring with long temporal coverage, and observations of very large dusty ring structures. Such activities should receive adequate funding and support.

V. Summary and Conclusions

We have reviewed recent advances in planetary rings research and presented a prioritized list of Key Science Questions and of Specific Action Recommendations, reflecting the results of a broad-based survey of professional rings scientists.

The highest priorities for exploration of planetary rings in the next decade include the successful completion of the Cassini Solstice Mission at Saturn, and the sending of spacecraft to Neptune and/or Uranus. On Earth, priority should be given to continued in-depth analysis of data already obtained and to PDS archiving and services to support that analysis, to theoretical and laboratory work that provide essential support to observations, and to developing technologies to facilitate more robust future missions to the outer solar system.

The Planetary Science Decadal Survey must include strong support for an integrated program of rings science as an essential component of studying planetary systems in general.

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