

# Dust Hazard Management in the Outer Solar System

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**Most robotic missions to the outer solar system must grapple with the hazards posed by the dusty rings of the gas giants. Early assessments of these hazards led simply to ring avoidance due to insufficient data and high uncertainties on the dust population present in such rings. Recent approaches, principal among them the Cassini dust hazard management strategy, provide useful results from detailed modeling of spacecraft vulnerabilities and dust hazard regions, which along with the range of mission trajectories are used to to assess the risks posed by each passage through a zone of potential hazard. This paper shows the general approach used to implement the analysis for Cassini, with recommendations for future outer planet missions.**

## I. Introduction

All of the outer planets have ring systems, and most of them are believed to contain some dust which is large enough to pose a hazard to spacecraft via hypervelocity impacts onto or near sensitive components. Any mission traveling to the outer planets must contend with this hazard potential, and demonstrate that their trajectory either does not pass near these rings, or conduct a detailed analysis to prove that the risks of particle impacts is within acceptable limits.

The ring systems of the outer planets is shown qualitatively in figure 1 and more quantitatively in figure 2. Saturn's main ring system is naturally most well known and contains by far the most material; no mission, past or future, would plan to cross through the main rings at high speed. Even the divisions and gaps in Saturn's main rings contain sufficient material to pose a significant hazard to any spacecraft flying through them.<sup>1</sup>

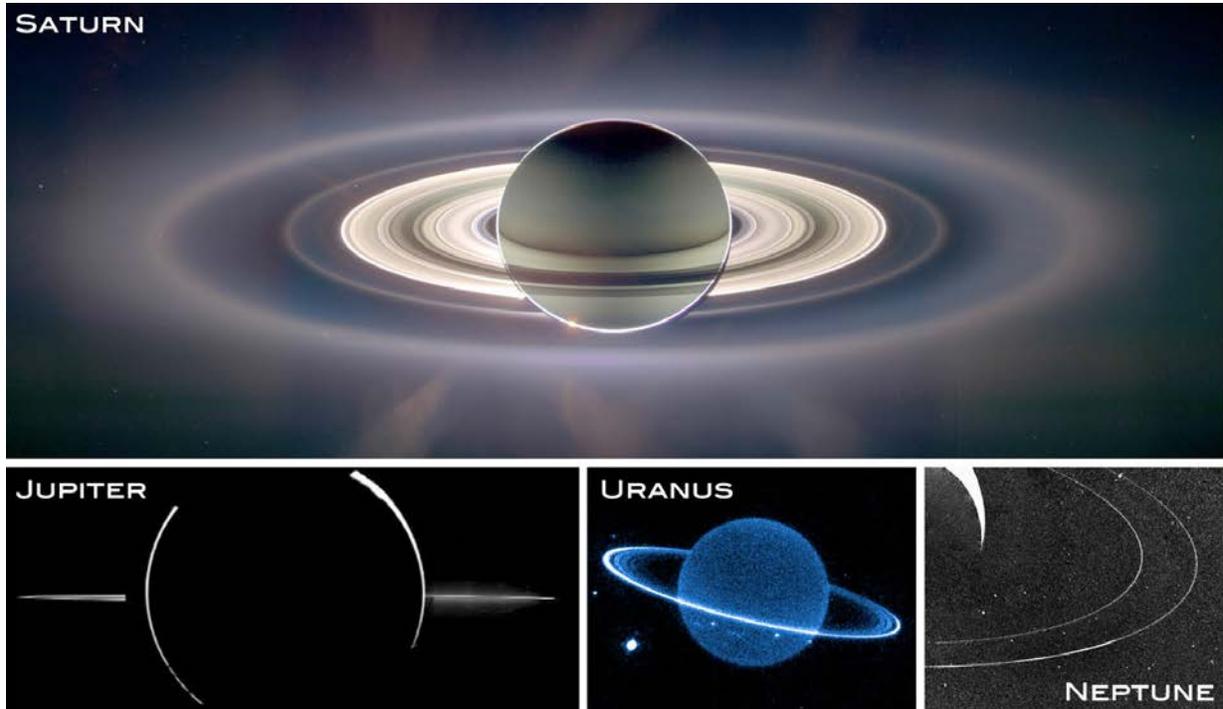


Figure 1. Outer planet ring systems; Uranus image credit: W.M. Keck, de Pater / Hammel

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However, the faint rings of Saturn seen clearly in figure 1, as well as the rings of Jupiter, Uranus and Neptune have, in some areas, dust that is sufficiently small or in low enough abundance (or both) to render those areas safe for spacecraft to cross. Saturn's E ring, which is the outermost and most visible faint ring of Saturn's system in figure 1, extends over so wide an area that it is nearly impossible for spacecraft to orbit near Saturn without crossing through it. Fortunately, the E ring is supplied by the plumes of Enceladus and is believed to harbor no particles above several microns in size.

Figure 2 plots the outer planets' planetary rings side by side in terms of planetary radii from the center of each planet. Also shown is the Roche limit at 2.44 radii (dotted line; assumes similar densities for planet and satellite / dust), within which bodies of material tend towards breakup and ring formation, and beyond which bodies of material tend to coalesce to form moons. Saturn's E ring, supplied by the plumes of Enceladus, and its G ring, supplied by its parent body Aegaeon (discovered by Cassini) and stabilized by a 7:6 resonance with Saturn's satellite Mimas, are some of the exceptions to the latter tendency. It is well known that many satellites have the theoretical ability to support material in "horseshoe" or "tadpole" orbits at the same radius through gravitational three-body dynamics, a good example of which is the trojan asteroids which librate about the L4 and L5 stability points (the centroids of "tadpole" orbits) of Jupiter. Also plotted on figure 2 are notable ring-plane crossings for some missions including Galileo ("Gal"), Pioneer 11 ("P11"), Voyager 2 ("V2"), and Cassini ("CAS") which are discussed later. Cassini's two ring-plane crossings are for Saturn Orbit Insertion (the upper) and its last "proximal orbits" mission phase (the lower). Cassini has made and will make many crossings between 2.5 and 4.0 R<sub>s</sub>, too many to be illustrated here.

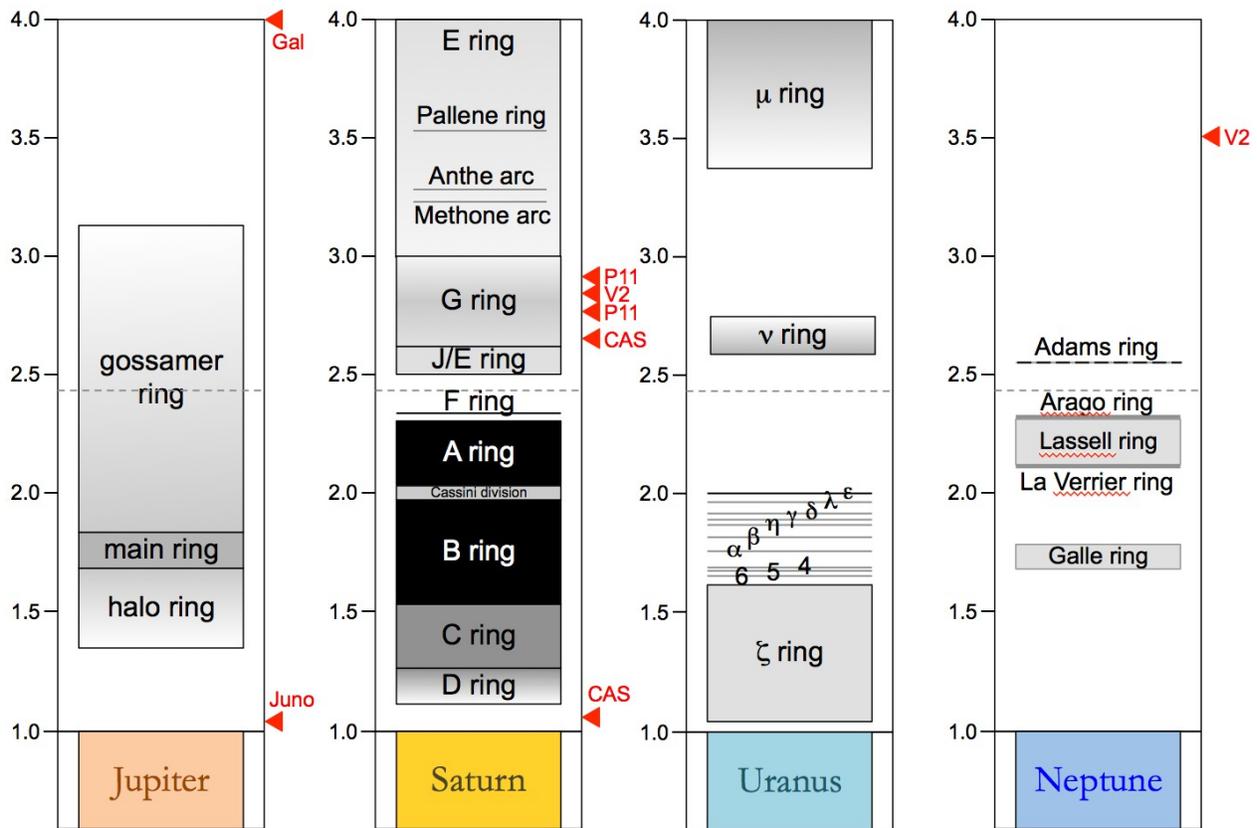


Figure 2. Ring systems of the outer planets, plotted in distances in planetary radii from the planet center

## II. Historical Rings Encounters (Pre-Cassini)

The outer planets have been visited by a variety of spacecraft to date, some of which are responsible for the discovery of the fainter rings shown in figures 1 and 2. In the following subsections, distances will be referred to by R<sub>x</sub>, where x is the first initial of the relevant planet, indicating distances in radii from the planet's center.

It is interesting to note that in the early days of outer planets exploration, dust in the asteroid belt was also thought to pose a potential hazard to spacecraft: "The Pioneers would be the first spacecraft to fly through the asteroid belt; there was no significant chance of hitting a large asteroid, but hitting a few hundred grains of sand would be almost as bad, and nobody knew how many small particles might lurk undetected in the belt."<sup>2</sup> As no

significant hazardous dust unique to the asteroid belt has been detected to date from many crossings through the region, this is no longer a concern.

### A. Jupiter

Pioneer 10 was the first spacecraft to visit Jupiter in 1973<sup>3</sup>, and made its closest approach at 2.9  $R_J$ , but 14 degrees below the ring plane and therefore far from Jupiter's ring system, and made no detection of ring dust. Pioneer 11 visited Jupiter in 1974 and flew closer, at just 1.6  $R_J$ , but south of the equator as well and also did not cross near the ring system<sup>4</sup>.

It was not until Voyager 1's encounter with Jupiter in March of 1979<sup>5</sup> that the Jovian rings were discovered. Voyager 1 closest approach was at 4.8  $R_J$ , too distant to encounter the rings in situ, but the spacecraft imaged them at high phase on departure, and the ring's discovery was quickly announced in the June 1979 issue of *Science*. Voyager 2 encountered Jupiter several months after Voyager 1, in July 1979, but at an even greater distance of 10.1  $R_J$ , resulting in less radiation exposure and a slower flight to Saturn<sup>6</sup>.

Ulysses, a joint NASA/ESA mission launched to study the Sun (particularly at high latitudes), swung by Jupiter in February of 1992 to increase its heliocentric inclination to 80 degrees, but flew by Jupiter at a distant 6.3  $R_J$  and did not pass close to the ring system either.

Galileo, despite eight years in the Jovian system from 1995-2003, passed no closer than 4.0  $R_J$  to Jupiter - during its Jupiter Orbit Insertion maneuver - until its end of mission in 2003 where it plunged into the planet, though at 22 degrees northern latitude, far above the ring system<sup>7</sup>. As with earlier spacecraft, Jupiter's intense radiation environment has been a strong influence in keeping spacecraft far from the planet and therefore away from potential ring hazards.

Cassini flew by Jupiter at a distance of 136  $R_J$  in December 2000, and New Horizons passed Jupiter in February 2007 at a distance of 32  $R_J$ .

In summary, no spacecraft to date have passed anywhere near Jupiter's ring system. That task of analyzing Jovian ring hazards has fallen squarely upon the Juno mission, whose mission plan contains many orbits crossing Jupiter's ring plane at close distance, and is discussed later in this paper.

### B. Saturn

Pioneer 11 was the first spacecraft to visit Saturn in September 1979. Initially, its aimpoint was a subject for much debate amongst the project. As researched by Henry Spencer and published in the *Canadian Space Gazette*<sup>2</sup>: "The more daring trajectory would take Pioneer inside the rings, with closest approach about halfway between the cloud tops and the innermost edge of the main rings. This was a relatively dangerous area, because there was known to be at least one faint ring [the D ring] inside the main ones. The estimated probability of spacecraft survival ranged from over 99% to under 1%, depending on whose ring-density model you believed. The payoff was a unique opportunity to observe Saturn and its magnetosphere up close, using an old spacecraft whose useful life was nearly over anyway. However, actually losing the spacecraft at the ring-plane crossing would considerably reduce the data return. After a long debate, the principal investigators who ran Pioneer's instruments voted 11 to 1 in favor of this 'inside' mission. The more conservative 'outside' plan specified two ring-plane crossings, both well outside the visible rings. The chosen distances for the crossings matched the flyby distance needed for Voyager 2 if it were to reach Uranus. The Voyager planners, given a unique and irreplaceable opportunity to visit two more planets, badly wanted to know if that distance presented any risks to their spacecraft. Such a flyby was also much safer for Pioneer, assuring Saturn data return after ring-plane crossing and also providing for a continued mission on into deep space. The final decision was made at NASA Headquarters: using Pioneer as a pathfinder for the Voyager Uranus-Neptune mission was more important than getting maximum return from the Pioneer flyby alone. Pioneer would take the relatively safe 'outside' trajectory."

Though thought to be "relatively" safe at the time, Pioneer 11 passed through the fringes of Saturn's G ring twice, at a distance of 2.8 and 2.9  $R_S$ , and detected subtle but persistent signatures in Saturn's magnetosphere, though these traces were not positively linked to a potential ring until after the G ring's discovery by Voyager 1. It is curious to consider that in hindsight, while the bulk of Saturn's D ring is more densely populated with dust than Saturn's G ring, there exists an approximately 3,000 km wide region between the D ring and Saturn's upper atmosphere that is likely to have been safer than Pioneer 11's crossing locations. Voyager 1 would go on to image Saturn's G ring in one single picture during its Saturn encounter in November of 1980 and is therefore credited with the discovery. Voyager 1's two ring plane crossings were placed at the orbits of the satellites Titan and Dione<sup>8</sup>; though the spacecraft passed through the outer portions of the E ring, it never traveled close to any hazardous rings of Saturn.

Voyager 2, on the other hand, indeed went on to use approximately the same ring-plane crossing distance of Pioneer 11, simply using its two successful passages as evidence of safety (a small data set). With the knowledge of the existence of the G ring, but only the single image from Voyager 1 as an inexact guide to its location, the Voyager project chose a crossing distance of 171,300 km from the center of Saturn (2.84  $R_S$ ). As stated in the Voyager 2

Saturn Press Kit<sup>9</sup>: “Voyager 2 crosses the potentially hazardous ring plane only on its outbound leg... just 1,200 km (745 mi) outside the orbit of the G-ring which is only approximately located by a single Voyager 1 photograph. (Voyager engineers expect the spacecraft to clear the G-ring by 1,200km or 745 mi.)”

Voyager 2 did not. As is now understood, the G ring extends from 2.6  $R_s$  to 3.0  $R_s$  with a sharp peak at the orbit of its parent body Aegaeon at 2.8  $R_s$  - nearly the exact location Voyager 2 chose for its crossing. Nevertheless, the spacecraft survived the passage (calculations in hindsight assess the likelihood of a successful passage at ~97%) and the Voyager 2 press kit at least illustrates an analysis on the part of the project to locate a potentially hazardous ring and implement a trajectory specifically designed to avoid it.

### C. Uranus

Uranus’ rings were definitively discovered via Earth-based airborne observations in March of 1977, nearly nine years before Uranus’ only in situ visit by Voyager 2, making them the second ring system to be discovered (after that of Saturn). (Notes by William Herschel in 1789 indicate that he suspected a ring to be present, but the lack of similar observations by hundreds of astronomers over many years thereafter casts doubt as to whether he indeed saw a ring of Uranus, and his observation is generally considered unlikely.)

Voyager 2 in 1986 passed no closer than 4.6  $R_u$  to Uranus and therefore not close to its ring system<sup>10</sup>. Observations by the Hubble Space Telescope since Voyager 2 increased the total number of Uranian rings to 13, including the outermost ring which shares its orbit with a small satellite (“Mab”).

### D. Neptune

Neptune’s rings were predicted in the 1970s and 1980s via dozens of stellar occultations, but ground-based results were inconclusive; structures of some kind clearly existed orbiting Neptune, but its features remained a mystery. (Like Uranus, rings around Neptune were reported long ago, by William Lassell in 1846, but as with Herschel, his claim was never confirmed and the observation also considered unlikely.) Voyager 2 is credited with the definitive discovery during its flyby in 1989.

Voyager 2 was aimed to pass close to Neptune’s suspected ring system, as stated in its encounter press kit: “Scientists [believe] that Neptune must be orbited by partial rings, or ring arcs, that are most likely composed of dust or pebble-sized material.... Voyager 2’s flight path carries the spacecraft close to the outermost set of possible ring arcs... the flight path can be adjusted as late as 10 days before the closest approach to Neptune in the event more distant ring arcs are discovered.”<sup>11</sup> Voyager 2’s two ring plane crossings were placed at 3.5  $R_n$  and 4.2  $R_n$ , indeed outside the Neptunian ring system. Nevertheless, particles on the order of 5-10 microns were detected by the Voyager 2 Plasma Wave instrument<sup>12</sup>, with a size uncertainty of a factor of 2-3. These particles are generally too small to constitute a hazard to spacecraft.

## III. Cassini Dust Hazard Management

Given the relative lack of missions conducting ring crossings with advanced knowledge of their properties, the burden fell to the Cassini project, whose spacecraft has been orbiting Saturn since 2004, to lead the first thorough ring hazard assessment for an outer planets mission. This is to be expected from the natural progression of the exploration of such rings: it is primarily in-situ visitation which is capable of providing details sufficient to form ring models of adequate certainty for spacecraft safety assessments, and Cassini is the first mission after those initial in-situ visitations to spend sufficient time around its target body within the ranges of hazardous rings. Before Cassini, projects either lacked information about such rings or possessed data so recent or limited that they could only steer their spacecraft away from the rings altogether via analyses confined to trajectory and geometric assessments.

Cassini’s early ring hazard assessments were performed during project formulation through development in the early 1990s by Neil Divine at JPL. After Divine’s early death in 1994, that body of work fell primarily to the author, who still holds the position of cognizant engineer for dust hazards on the project.

Cassini never had plans to penetrate the main rings of Saturn. Even the so-called gaps or divisions in the main ring system are far too dangerous for Cassini to penetrate, as contended before arrival and confirmed by imaging and occultation data from Cassini. However, Saturn’s E, G, and D rings, as well as the coorbital regions of some satellites, were possible regions for traversal and posed a potential hazard to the spacecraft.

### A. Ring Modeling

In 1995, in part at the urging of the author, a Ring Hazard Workshop was held at the Ames research center in Mountain View, CA and was attended by the bulk of the scientists leading the field of Saturnian rings and dust – nearly all of which were already associated with the Cassini project. The purpose of this workshop was to review the

scientists' understanding of the abundance and size of material outside the main rings of Saturn. The available data examined included measurements from the Pioneer IPP and charged particle instruments and in-situ measurements of micrometeoroid impacts; Voyager 1 and 2 remote science by the cameras, star trackers, and LECP data, and in-situ measurements by the PWS, PRA, and PLS instruments; Earth-based IR and visible photometry, photography and CCD imaging; and theories on constructive and destructive processes, dynamical stability of small particles, photometry and charged particle dynamics. New data and analysis of new and old measurements of note presented at the workshop included:

- New photometric observations obtained during the 1995 Saturn ring plane crossings by the Earth and Sun
- New particle properties in the G and E rings from new and revised analyses of impacts on the Voyager 1 and 2 spacecraft
- New analysis of magnetospheric microsignatures associated with the orbits of Mimas and Enceladus
- New theoretical models of Saturn's E ring
- New theoretical and numerical modeling of stable horseshoe and tadpole orbits, and quickly cleared "chaotic, crossing" orbits
- New theoretical and numerical modeling of debris belts as sources and sinks of particles

Based on the results from that workshop, ring models were developed that could be used (along with spacecraft vulnerability information) to estimate the hazards of crossings through Saturn's faint rings. These models have been updated via regular discussion in many Ring Working Group sessions of the thrice-yearly Cassini Project Science Group meetings, where new data and analysis have been presented from a variety of Cassini instrument measurements in orbit. Among them are the Cosmic Dust Analyzer, the Imaging Science Subsystem, the Visual and Infrared Mapping Spectrometer, and the Radio and Plasma Wave Spectrometer.

Overly conservative particle models, such as Divine's early "large particle model" where the majority of particles were modeled precisely at the minimum size dangerous to Cassini, were considered during formulation. Such severe monodispersions, where the bulk of the detected (imaged) dust is lumped into a size range most inconvenient to the mission, were guaranteed to severely degrade science return by eliminating a substantial portion of the Saturnian environment for exploration. This issue traces closely to the Pioneer 11 targeting debate mentioned earlier, where the risk to the spacecraft was seen to vary widely depending on which particle model was used. One of the prime science goals of Cassini has been to characterize the dust environment of Saturn, and its in-situ measurements would have been of little value if Cassini avoided regions which posed any risk, no matter how small. Moreover, such particle distributions are simply not plausible.

After much discussion within the project and scientific community, common sense indicated that the project should develop and rely on the most plausible models available, accepting that some were initially based on incomplete or conflicting measurements and/or theory. Where too little data existed even to develop a plausible model, but the presence of dust was believed possible, upper limits on the maximum level of debris that were as yet undetected were implemented. In some cases these were nothing more than gross upper limits on the amount of material which could be present. Since the models were expected to change as our understanding of the environment matured – and all of them have indeed changed with time during Cassini's study of Saturn's dust environment – the analysis techniques (i.e. the software tools and analysis and reevaluation process) were designed accordingly. Furthermore, priority was placed on the collection and rapid processing of new measurements to keep the dust analyses up to date. Fortunately, none of the dust models have yet exhibited massive change, save for a few satellite coorbital dust models which have gone away completely.

## **B. Spacecraft Vulnerability Assessment**

The analyses required to estimate risk to the spacecraft also required a detailed knowledge of the spacecraft layout, namely the vulnerability of all external surfaces to dust impacts, the locations of all critical hardware with respect to these external surfaces, and the mechanism by which impacting (or spalled) material may reach this hardware.

Following a detailed study of blueprints of the Cassini spacecraft, and discussion with flight systems engineers and hypervelocity impact specialists, select areas of the spacecraft were identified as most sensitive to particle impacts. A large factor in selecting these areas is the behavior of hypervelocity impacts and intermediate insulators. When a particle strikes any surface, even a surface that may seem superficially flimsy like thermal blanketing, it vaporizes into a shower of many smaller particles (generally an order of magnitude or more smaller than the original particle). For setback distances more than a few centimeters, even thermal blanketing provides substantial protection of any surface it shields. Since thermal blanketing covers the bulk of the spacecraft, and all critical systems behind thermal blanketing are also shielded by a second surface (e.g. propellant tanks behind the tank wall), the only components that are able to drive the dust hazard analysis are those not shielded by blanketing – in other words,

protected by only one surface, or none - and it is these surfaces that drive the computations. The single set of surfaces that alone drives the spacecraft vulnerability is select areas of the electronics bus.

Impacts on some areas of the bus can cause loss of mission, because the bus is not protected by thermal blanketing but typically by one layer of aluminum plating and louvres which are often open (see figure 3). The impact destruction mechanism is an unimpeded particle striking the outer bus aluminum plate and either penetrating through the plate to the electronics beyond, or spalling off aluminum fragments from the backside of the plate which then shower upon the components on the other side (either case produces deadly fragments that may be capable of destroying electronics). At a few locations around the bus, both strings of critical computing hardware are physically side-by-side and can therefore both be taken out with a single particle hit. The minimum particle size/velocity that could cause fragments to shower upon the electronics is 0.68 mm at a velocity of 20 km/s.

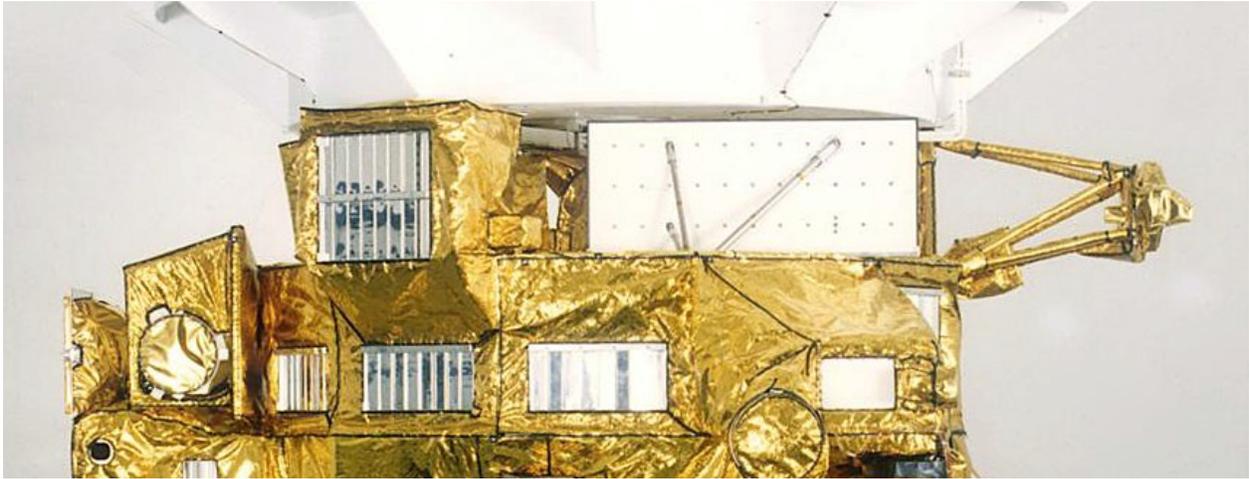


Figure 3. Cassini electronics bus (lower center). The Langmuir probe extends outwards at right, the top of the Remote Sensing Pallet is at left, and the High Gain Antenna (white) is at top. The bright metallic areas are louvres which, if open, would allow dust to strike one surface of aluminum shielding behind which lie the electronics.

The other spacecraft components that are analyzed for mission loss or degradation are the redundant main engine nozzles (see figure 4).



Figure 4. Cassini Main Engine Nozzles

Particle impacts can spall, pit, or penetrate the sensitive disilicide columbium coating which the engines require for proper operation. Testing and failures of space shuttle nozzles of a similar design (but much larger than Cassini's main engines) at the White Sands Test Facility revealed pitting, scarring and catastrophic burn-throughs. The failure

of one nozzle may be catastrophic and cause the failure of the redundant nozzle, but there is no data available on the exact likelihood of this occurring. However, the project acknowledges the possibility that a single hit causing the loss of one nozzle may lead to the loss of both. Loss of the main engines alone does not cause end of mission, but severely limits the orbit geometries available to the mission and ensures that some scientific objectives will not be met (the extent of which is a function of how far into the mission the engines are lost).

The main engine nozzles are sensitive to particle sizes as small as 42  $\mu\text{m}$  at impact speeds of 20km/s. These are the smallest particles which can cause pitting on the inside of the nozzle. As compared to the electronics bus minimum particle size of 680  $\mu\text{m}$  at the same speed, it is clear that the nozzles are far more sensitive (though again, their loss does not necessarily cause end of mission). Late in spacecraft development, this main engine nozzle vulnerability was discovered, and this led to the addition of a main engine “baby buggy” cover to be used to protect the nozzles (see figure 5). This cover has been used several dozen times since launch with continued operation in the Saturnian system (it was originally conceived for protection from micrometeoroids in the inner Solar System environment).

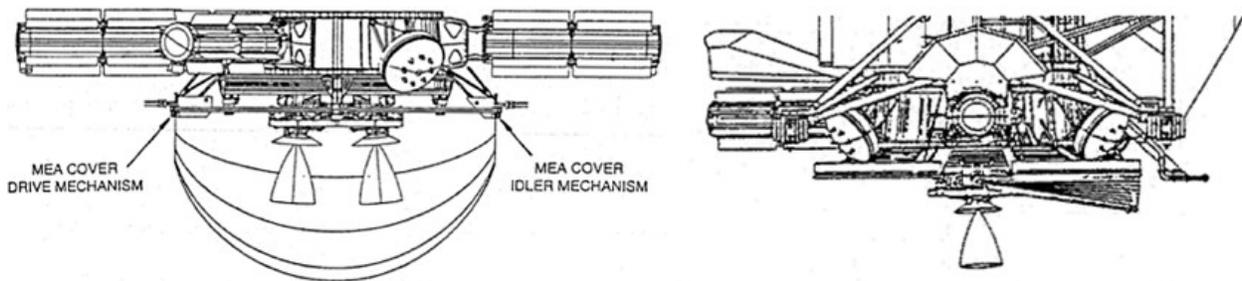


Figure 5. Main engine cover mechanism. Note that figure 4 was taken before installation of the cover.

### C. Hazard Modeling and Mitigation

And as with most scientific and engineering endeavors, neither Saturn’s ring environment nor the spacecraft’s vulnerability to hypervelocity impacts are understood perfectly. High-velocity impact physics is a difficult and only partially explored field, and the testing required for thorough knowledge of the physics with materials used to fabricate the Cassini spacecraft was found to be cost-prohibitive. Therefore, analogy and testing with as-similar-as-available materials and velocity profiles was applied. Furthermore, the particle environment is not perfectly known; despite the measurements made by Voyager 1 and 2, it is fair to say that the Saturnian faint ring system was poorly understood prior to Cassini’s arrival. That was a major scientific reason why Cassini was sent to Saturn in the first place – to explore its dust environment. Dust hazard analysis for Cassini in general has been a classic mission planning problem – to analyze risks and options and make critical project decisions in the midst of significant uncertainties and change.

Both the ring models and vulnerability assessments were implemented in a software tool used by Cassini to estimate the impact hazards for any candidate trajectory leg (using trajectory files as inputs). The software computes total particle fluences for any ring crossing, and these fluences are assessed one by one to determine what protective measures, if any, are warranted. These measures include:

- Redesigning the trajectory to avoid the region altogether
- Orienting the spacecraft so that the High-Gain Antenna is pointed into the dust direction
- Closing the main engine cover

The cost of the first strategy is very sensitive to both the spacecraft’s orbit, and the size and proximity to Saturn or targeted flybys of the debris regions in question. Dust crossings are more likely in low-inclination orbits, which are often used in conjunction with close periapses to get close flybys of the icy satellites. These orbits are typically highly constrained and added maneuvering for dust hazards has high costs both in propellant and science. Nevertheless, a number of cases have been analyzed in Cassini’s tour and trajectory redesigns were made for several orbits, including one that – without such analysis – would have unknowingly sent the spacecraft through the core of the G ring. These analyses have also been an important part of the extended mission tour design.

The less costly second strategy involves controlling the spacecraft’s orientation to protect the sensitive spacecraft areas from the incoming particles. The high gain antenna (HGA) is relatively insensitive to impacts of millimeter-sized or smaller particles which dominate the particle distributions. Even the antenna feeds can tolerate a peppering of millimeter-sized holes with almost no loss in transmission capability. The wavelengths Cassini uses for communication, RADAR and radio science are long enough that millimeter-sized holes in feeds or reflective surfaces cause almost no appreciable degradation, much like the mesh on the front of microwave ovens. The HGA

therefore constitutes a protective surface with significant setback distance and reduces the impact risk to insignificant levels. Needless to say, orienting the HGA to the incoming particle direction may compromise some science gathering, as Cassini's instruments are body-fixed and HGA orientation would constitute a conflict to targeted observations.

The third strategy of cycling the main engine cover is executed with some regularity, with 86 total cycles planned throughout the Cassini mission. This strategy does not protect the electronics bus, but does have the advantage of not conflicting with science collection, and is used for less hazardous crossings where the risk to the electronics bus is small (but unacceptably high for the main engine).

#### D. Results of Hazard Analysis

The first hazard analysis performed with the above approach was for Cassini's Saturn Orbit Insertion in June of 2004. Unlike Pioneer 11, Cassini did not consider flight between the rings and the planet a feasible option. Divine's work recommended a crossing location near 2.6  $R_s$ , between the outer edge of the main rings and the G ring, but a complete reassessment was warranted. A variety of other, nearby dusty regions was suspected, along with material sharing the orbit of the coorbital satellites Janus and Epimetheus (which was confirmed) as well as the orbit of Mimas (which was found not to be present). After a detailed assessment, along with multiple runs of the Cassini software tool, Divine's selected location was confirmed (see figure 6). This location had the advantage of being close enough to Saturn so as not to incur a propellant cost for a more distant orbit insertion, but also avoided the orbits of both Janus/Epimetheus and Mimas, as well as the G ring - though by rather small margins of a few thousand km from all of them. The Cassini navigation team assured the project that the targeting would easily be accurate to this level, and indeed hit the ring-plane crossing aimpoint to within a few tens of km.

Nevertheless, it seemed prudent to take all possible precautions for orbit insertion, so the HGA was also turned "into the wind" for both Cassini's ascending ring-plane crossing prior to the insertion burn and the descending crossing afterwards. Both of Cassini's crossings were designed at the same location, similar to Pioneer 11.

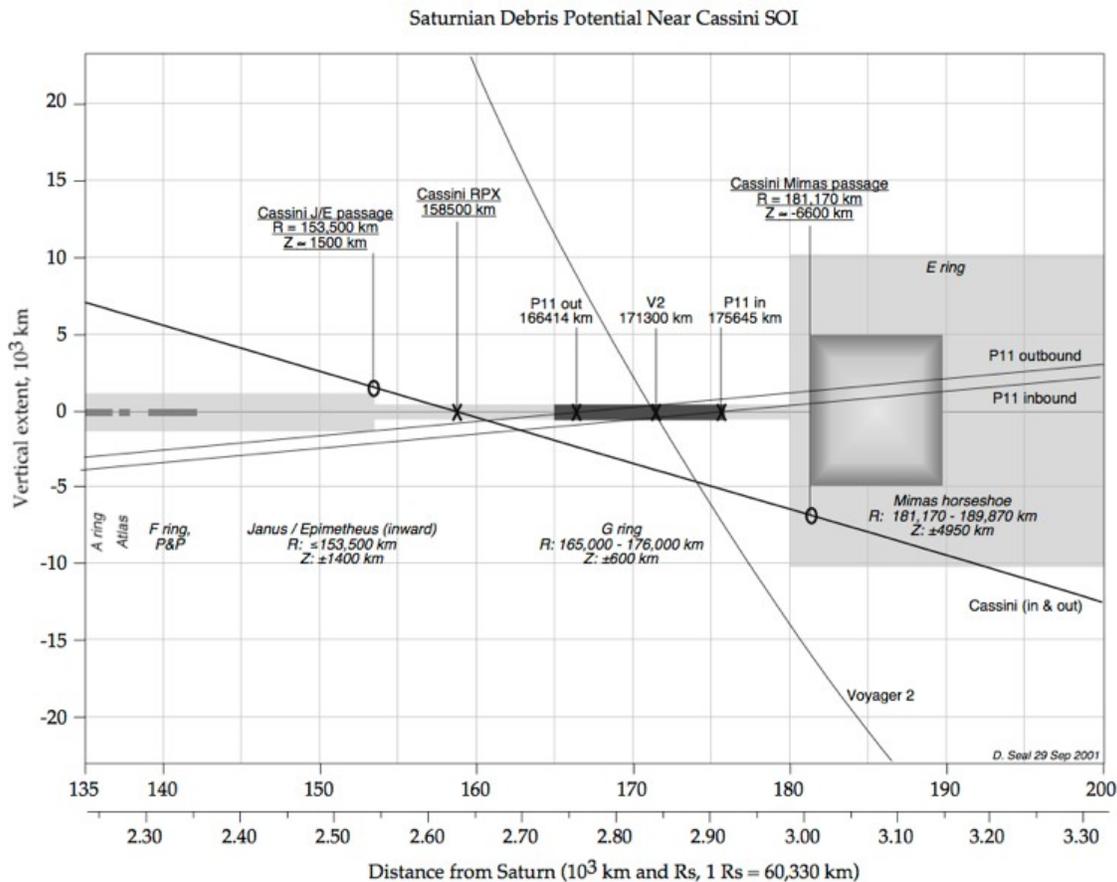


Figure 6. Cassini Saturn Orbit Insertion planning graphic (2004). Many of the dimensions of the dusty regions have since been updated or eliminated altogether, so this graphic should only be considered as anecdotal; the ring-plane crossing locations of Pioneer 11, Voyager 2, and Cassini (for orbit insertion) are accurate.

As of the publication of this paper, much scientific analysis has been done on Saturn's dusty rings with Cassini data, and the hazard assessments and protective measures are considered to be reliable, though they are revisited in Rings Working Group and project planning meetings with regularity. The combined as-flown and predicted hazards, with and without protective measures, are shown in tables 1 and 2. Table 1 lists the hazards by mission phase, whereas table 2 shows the hazards by geometric region. Note that the E ring (large) region represents a core region of larger particles of the E ring closely confined to the ring plane and near Enceladus. The vast majority of the E ring is believed to be comprised exclusively of small (~ few microns in size) particles and not hazardous. However, there is still a possibility (though remote) of larger particles in the core of the E ring, and this model accounts for that population.

Both tables illustrate the improvements from implementing protective measures, particularly via protection via the main engine cover. Risk reductions to the spacecraft electronics bus are more moderate, primarily due to the many crossings at low risk accumulating over time. However, the risk results are still within the project-defined requirements of 1% environmental risk per year of mission.

Table 1. Cassini risks from dust crossings, by mission phase

	Potential risk (no protection)		Actual risk assumed (with protection)	
	Spacecraft	Main Engine	Spacecraft	Main Engine
Prime mission (2004-2008)	1.7%	21%	1.4%	2%
Equinox mission (2008-2010)	1.6%	22%	0.9%	1%
Solstice mission (2010-2017)	1.1%	19%	0.8%	1%
Totals	4.3%	46%	3.1%	4%

From table 2, the many crossings of Cassini through Saturn's dusty rings are seen, particularly of the potential (though unlikely) E ring "core" - due in large part to the many Enceladus flybys implemented by trajectory designers. There are also many crossings through the G ring, though all of these were through its outer reaches, and none through the core - implemented intentionally via trajectory design, in some cases at a propellant cost. The G ring clearly constituted the largest hazard to the spacecraft, and protective measures were assumed frequently.

Table 2. Cassini risks from dust crossings, by region

	No. of crossings	Potential risk (no protection)		Actual risk assumed (with protection)	
		Spacecraft	Main Engine	Spacecraft	Main Engine
2.47 Rs gap	9	0.2%	4%	0.2%	0%
Janus/Epimetheus	19	0.8%	13%	0.4%	0%
G ring	21	3.0%	24%	2.0%	1%
Methone arc	1	0.0%	0%	0.0%	0%
Anthe arc	0				
Pallene ring	25	0.4%	8%	0.4%	2%
E ring (large)	89	0.1%	15%	0.1%	2%
Totals	164	4.3%	46%	3.1%	4%

One of Cassini's principal discoveries was the plumes of Enceladus which supply the E ring. Close investigation of these plumes became a high scientific priority, but the potential hazards of large particles present in the plumes was immediately identified as a concern. The piecemeal equivalent of a new hazard workshop was conducted over the course of several Project Science Group meetings and project study groups, with the conclusion that there was no plausible mechanism by which the plumes could loft particles large enough to damage the spacecraft. However, this data was acquired, and trajectories through the plumes planned, in a stepwise fashion, sending the spacecraft first through the outermost reaches of the plumes, and only later (after that data was analyzed and assessments repeated) deeper into the plume environment. This approach is shown in figure 8.

Cassini's last weeks of life will finally see the spacecraft aimed (as was considered for Pioneer 11) between the rings and the planet in an exciting, never-before-envisioned 22-orbit mission phase, and investigation of the hazards posed by the inner reaches of Saturn's D ring are underway. Cassini measurements to date indicate a 3,000 km safe window between the inner edge of the D ring (where its brightness falls to the background) and Saturn's upper atmosphere. Nevertheless, further observations of this region are planned before the mission phase begins in 2017; reassessments will be performed prior to entering those orbits; and Cassini will orient its HGA to the incoming particle direction for the first few crossings and conduct analysis of impact data collected by the Radio and Plasma Wave Spectrometer to estimate the potential hazards of later crossings at other attitudes. Cassini is scheduled to enter Saturn's atmosphere permanently on September 15, 2017.

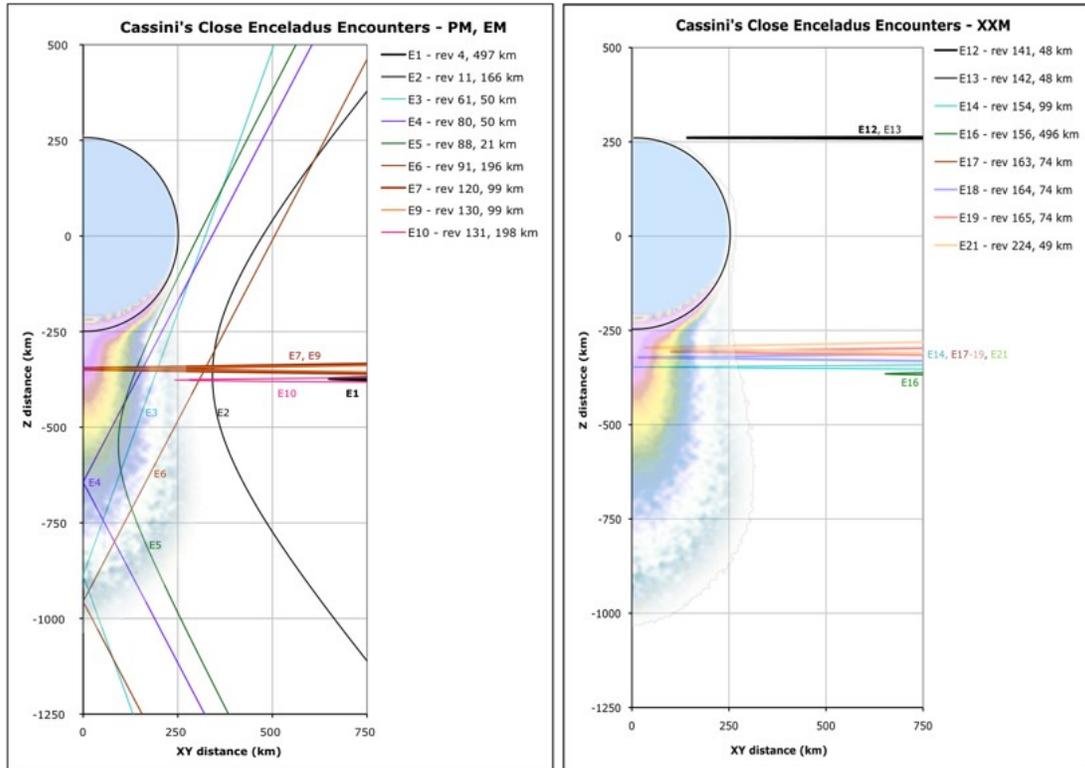


Figure 8. Cassini paths through Enceladus' plume, 2004-2010 on left and 2010-2017 (planned) on right. Note the stepwise process of traveling deeper and deeper into the plume, which was paired with analysis along the way.

Figure 9. Side view of Cassini's planned 22 proximal orbits. The D ring brightness has been artificially enhanced and is the lavender-colored feature at bottom center; likewise with Saturn's upper atmosphere at bottom right

## IV. Outer Planet Missions in Flight

Two missions to the outer planets are currently in flight, and discussion of the hazards they are likely to face, and analysis conducted to date, is included as follows.

### A. New Horizons

The New Horizons mission was launched in January of 2006 with an expected arrival at Pluto in July of 2015. Pluto has four known satellites; based on the prevalence of dusty rings around all four outer planets, as well as sharing the orbits of many satellites, the New Horizons project has conducted a hazard assessment led by Henry Throop. However, there is very limited data available, as with the Pioneer and Voyager missions which were similarly first to visit the outer planets. Therefore, this assessment took a similar approach as early Cassini analyses, computing an upper limit of dust present (integrated along a line of sight) based on scattered light around Pluto from Hubble observations. Furthermore, the dust model was likewise developed during a hazards workshop held in November of 2011 and attended by Pluto experts whose purpose “was to discuss possible collisional hazards... during [New Horizons] upcoming 2015 trajectory through the Pluto system.”<sup>13</sup>

In his white paper written after the conference, Throop states: “The New Horizons spacecraft’s nominal trajectory crosses the planet’s satellite plane at  $\sim 10,000$  km from the barycenter, between the orbits of Pluto and Charon. I have investigated the risk to the spacecraft based on observational limits of rings and dust within this region, assuming various particle size distributions. The best limits are placed by 2011 HST observations, which significantly improve on the limits from stellar occultations, although they do not go as close to the planet. From the HST data and assuming a ‘reasonable worst case’ for the size distribution, we place a limit of  $N < 10$  damaging impacts by grains of radius  $[> 0.2 \text{ mm}]$  [corrected from typo] onto the spacecraft during the encounter.”

This number  $N$  is above the project’s acceptable level of damaging impacts, though the analysis considers an impact on any portion of the spacecraft as equally damaging. Further analysis of the more sensitive spacecraft components may reveal this assumption to be conservative. Throop continues: “Continued studies with HST may improve our limit on  $N$  by a factor of a few. Stellar occultations remain valuable because they are able to measure  $N$  closer to the Pluto surface than direct imaging, although with a sensitivity limit several orders of magnitude higher than that from HST imaging.”

Based on this analysis, the project has assigned itself two actions: to continue observations of the Pluto environment via both Earth-based and New Horizons approach measurements to attempt to improve the knowledge of the dust environment; and the design and consideration of a “bail-out” trajectory which the spacecraft is capable of switching to up to about ten days before the flyby. The project has already been allocated a generous 34 orbits of time on the Hubble Space Telescope in June and July of 2012.

### B. Juno

The Juno mission to Jupiter launched in August of 2011 with arrival scheduled in July of 2016. As a mission focused on Jupiter’s interior structure via 33 orbits passing within 5,000 km of the cloud tops, hazards from Jupiter’s ring system are definitely an issue worth considering. Like New Horizons, there are no data sets that give direct information about the region of space through which Juno will be flying. Optical observations are frustrated by the glare of the planet which mask any features that might be there<sup>14</sup>.

Juno crosses Jupiter’s equatorial plane at 1.06  $R_j$ , which is extremely close to Jupiter and well within the identified inner boundary of the “halo ring”. However, there are theoretical arguments which favor the possibility that material from the main rings might work its way inward to Jupiter’s cloudtops. The worst-case scenario, considered unlikely, is that there may be an as-yet-undetected small satellite which could supply the Juno crossing environment with a significant dust population.

Doug Hamilton et al (reference 14) have done preliminary analyses without observational constraints aimed to calculate the loss rate of material from the main rings, a difficult task. This effort is still in work, but results so far show promising results towards a successful Juno mission, with very few large (tens of microns) particles expected at Juno’s ring-plane crossing distance.

## V. Conclusions

Projects which aim to explore the outer planets (such as ESA’s JUICE and NASA’s proposed Europa mission) that may be considering a family of trajectories that include passages through or near any ring systems should consider engaging in the following strategies:

- Enlist its science community to convene a rings workshop, gathering the best scientific minds of the era with expertise in ring studies, to meet and discuss the most recent data and analyses of the relevant ring systems

- Work with the leaders of the rings workshop to translate its conclusions into rings models - specifying abundance, size distribution, and geometric extent - that can be used for hazard analysis by the project
- Tap spacecraft engineers to assess the vulnerable areas of the spacecraft via a thorough review of its design, along with an understanding of hypervelocity impact physics; bring in hypervelocity impact and materials experts where necessary; also identify “safe” or “safer” orientations of the spacecraft with respect to the incoming dust direction that could be used to reduce the likelihood of a mission-ending event
- Gather the rings models and spacecraft vulnerabilities into a software or equivalent analysis package capable of simulating any candidate trajectory and computing fluences for all dust crossings
- Conduct the above studies (in a preliminary form, at least) in project development during the early stages of spacecraft design to identify any alterations that may be warranted, including (but not exclusively) the addition of protective blanketing or covers, additional shielding, or physical separation of redundant critical components that might otherwise have only one surface of protection (or none) separating them from open space
- Make early measurements and subsequent analyses of the ring systems - whether they be ground-based or in-situ observations by the project assets - a scientific priority where feasible
- Identify a single responsible cognizant engineer on the project who is comfortable with change and uncertainty and whose job it is to remain vigilant to dust hazards, reassess and promptly update rings models when new measurements are available, and ensure that protective measures are communicated and implemented correctly
- Include particle hazards explicitly in the project risk database, and track and report their status with regularity

### Acknowledgments

The author wishes to acknowledge Neil Divine (posthumously) for his groundbreaking and thorough hazard studies early in Cassini’s life cycle, Cassini project manager Robert Mitchell for his recognition of dust hazards as an issue deserving of consistent support, Dr. Jeff Cuzzi for his steady leadership at the Cassini Rings Hazard Workshop and of the Rings Discipline Working Group, Drs. Matthew Hedman, Mark Showalter, Larry Esposito, and Matthew Tiscareno for their many scientific studies for Cassini, Drs. John Spencer and Doug Hamilton for supplying hazard and trajectory data on other missions, and G. Mark Brown, David Nichols and Leslie Livesay at the Jet Propulsion Laboratory for supporting the author’s desire to bring this work to light.

Details on each of the Saturnian ring models, and the mathematics of Cassini’s ring hazard calculations are available from the author; due to space limitations, they could not be included here.

The preparation of this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under contract with the National Aeronautics and Space Administration.

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