Neptune Ring Science with Argo – A Voyage through the Outer Solar System

L. J. Spilker (JPL), C. J. Hansen (JPL), N. Albers (Univ. of Colorado), A. S. Aljabri (JPL), D. Banfield (Cornell), E. B. Bierhaus (LMA), M. Brown (CIT), J. E. Colwell (UCF), C. Chavez (UNAM, Mexico), F. Crary (SwRI), I. de Pater (UC Berkeley), M. Dougherty (Imperial College, UK), C. Ferrari (Univ. of Paris Diderot and CEA Saclay, France), G. Filacchione (INAF-IASF, Italy), R. French (Wellesley), M. Gordon (SETI Institute), E. Gruen, (Max Planck Institute, Germany), M. Hedman (Cornell), A. R. Hendrix (JPL), M. Horanyi (Univ. of Colorado), G. Hospodarsky (Univ. of Iowa), A. Ingersoll (CIT), Sasha Kempf (Max Planck Institute), K. Khurana (UCLA), B. Kurth (Univ. of Iowa), D. Landau (JPL), J. Lissauer (Ames), E. Marouf (San Jose State Univ.), A. McEwen (UAz), D. A. Paige (UCLA), C. Paranicas (APL),F. Postberg (Max Planck Institute, Germany), N. Rappaport (JPL), H. Salo (Univ. of Oulu, Finland), C. M. Satter (JPL), B. Schmidt (UCLA), M. Showalter (SETI Institute), T. R. Spilker (JPL), J. Stansberry (UAz), N. Strange (JPL), M. S. Tiscareno (Cornell), P. Yanamandra-Fisher (JPL)

Some earlier co-authors have recused themselves due to Decadal Survey panel obligations

Primary author contact: Linda J. Spilker, 818-354-1647, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, linda.j.spilker@jpl.nasa.gov

This white paper describes the Neptune ring science to be achieved by Argo (the Neptune ice-giant, Triton and Kuiper Belt Object science objectives are described in separate white papers)

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Executive Summary

Argo is an innovative concept for a New Frontiers 4 mission to significantly expand our knowledge of the outer Solar System. It exploits an upcoming launch window that permits a close Triton encounter during a flyby through the Neptune system, studies of the Neptune ring system, and then continues on to a *scientifically-selected* Kuiper Belt Object. The mission will yield significant advances in our understanding of evolutionary processes of rings and small bodies in the outer Solar System, in addition to providing an opportunity for historic advances in ice-giant system science. By carefully focusing scientific goals and optimizing the payload, Argo can provide paradigm-shifting science within the New Frontiers cost envelope. Given the challenges of distance and time for deep outer Solar System missions and the required scientific observations, Argo is the minimum-mission possibility. The combination of all these factors makes this mission well suited to be one of the top-ranked New Frontiers mission in the next planetary decadal survey.

I. Introduction

Beginning with the first discovery of Kuiper Belt Objects a quarter century ago, our understanding of the outer Solar System has undergone revolutionary changes. More recently – and with more import – is the realization from Solar-System-evolution studies that the locations of the outer planets have evolved significantly since their original formation. There is mounting evidence that Neptune, in particular, formed far closer to the Sun than its current remote location.

The Nice model, for example, posits that for the first several hundred million years after the formation of the planets, the outer Solar System was much more compact, with Neptune well inside 20 AU (Tsiganis et al. 2005). Evolution of the planets' orbits eventually led to Saturn and Jupiter crossing their mutual 2:1 mean motion resonance. The resulting perturbation to Saturn's eccentricity strongly perturbed the orbits of Uranus and Neptune, leading to the current configuration of giant planets. In many N-body simulations of this evolution, Neptune was the inner ice giant prior to the resonance crossing: it may have formed within 15 AU of the Sun, only a few AU exterior to the primordial Saturn. The Nice model satisfactorily explains many Solar System features, including evidence of a Late Heavy Bombardment (Gomes et al. 2005), the origin of the Trojan asteroids (Morbidelli et al. 2005), the current configuration of the giant planets (Tsiganis et al. 2005), and possibly the origin of Saturn's rings (Charnoz et al. 2009).

The capture of Triton by Neptune may have occurred during this planetary reshuffling, as well as intense impact bombardment of any of Neptune's primordial regular satellites. The consequences of a Late Heavy Bombardment on Neptune's moons include alteration of the size distribution of moons through fragmentation, impact cratering, and disruption of moons to form rings. Satellite disruption, as well as tidal capture and disruption of comets, should lead to significant rings around Neptune. Indeed, the *absence* of a massive ring system at Neptune coupled with the presence of one at Saturn is one of the more significant problems posed by the Nice model in terms of planetary ring formation (Charnoz et al. 2009).

In this new context, Neptune couples tightly with Saturn in the formation and evolution of the outer Solar System. With a detailed study of the Saturn system completed by Cassini, a new examination of the Neptune system is needed to answer the new questions raised by our improved understanding of the evolution of the outer Solar System and its coupling with the primordial and present-day Kuiper Belt.

Given these advances, it is frustrating that no missions to this realm of the Solar System are planned or expected for decades. Indeed, with the current notional timeline (e.g. *Science Plan for NASA's Science Mission Directorate*, 2007), our next glimpse of Neptune will not occur for at least half a century after the Voyager 2 flyby in 1989. Voyager's technology was already more than a decade old at the time of that encounter, and technological advances since the 1970s can provide significant scientific advances with "just flybys" at "old" targets as shown by the recent passages of New Horizons by Jupiter (*Science*, 318, 215-243, 2007) and of MESSENGER by Mercury (*Science*, 321, 58-94, 2008). Missions to Neptune have been stymied by a perception that an orbiter (i.e., a Galileo- or Cassini-like flagship mission) is required for major scientific progress. Yet nearly all aspects of the Neptune system that we can measure from Earth have changed dramatically since Voyager, including Neptune's atmosphere, its ring system, and the atmosphere of its large moon Triton. Thus, a spacecraft equipped with simple yet modern technology, on a flyby trajectory past Neptune, will yield significant new ice-giant-system science.

A Neptune flyby also provides a critical advantage over a Neptune orbiter: it gives us the opportunity to explore a ***scientifically-selected Kuiper Belt Object*** (*KBO) because of the trajectory's large bending angle due to massive Neptune.* This allows access to a vast cone of space, yielding numerous potential targets among the known KBO population. Observations of the characteristics of the KBOs have opened a window into the formation and early evolution of the Solar System.

Argo is an innovative mission concept for New Frontiers 4: it flies by Triton and Neptune, and continues on to explore a Kuiper Belt Object. A launch opportunity to the outer Solar System via Neptune opens in 2015 and lasts through the end of 2019, with backup options in 2020. It allows trajectories with reasonably short trip times to Neptune (8-11 years) and the Kuiper Belt (an additional 3-5 years), as well as low Triton approach speeds <17 km/sec (comparable to Voyager). We envision a New Frontiers mission that employs current spacecraft technology (analogous to New Horizons); and a simple yet capable payload, also suggested by the New Horizons and/or the MESSENGER payload.

II. Neptune's Rings and Inner Satellites

The Argo science payload and flyby trajectory offer a unique opportunity to increase our understanding of the unusual Neptunian ring system (Fig. 1) and its retinue of small inner satellites. Ring-moon systems were once perceived as stable and unchanging for time scales of at least 10^6–10^8 years. New, higher-quality data from Cassini, Hubble and ground-based telescopes are painting a different picture, in which the systems evolve over years to decades. The knowledge gained by studying this system of rings and satellites will be applicable to ring systems and planetary disks that occur elsewhere in the universe.

The study of planetary ring dynamics has been instrumental in advancing our understanding of the processes at work in the primitive solar nebula during the Solar System's formation. Voyager images revealed exquisite complexity and structural variety in ring systems (Smith et al. 1989, Porco et al. 1995). It has the additional scientific interest of being the most remote and least-known ring-moon system in the Solar System and the only other ring system besides Saturn's known to possess relatively stable arcs.

Neptune's rings were discovered by stellar occultation in 1984 (Hubbard et al. 1986), but their exact arrangement was unknown until 1989, when Voyager's cameras revealed 5 continuous rings, two broad (Galle ~2000 km and Lassell ~4000 km wide) and 3 narrow (Adams, Le Verrier, and Arago) as well as a system of 3 to 5 arcs confined within a 40° sector of the otherwise fainter Adams ring (Smith et al. 1989). Nicholson et al. (1995) extrapolated the arcs' motion backward from the Voyager epoch and showed that all prior occultations were compatible with them, implying a longevity of > 5 years. Without a confinement mechanism, arcs should disperse in a matter of weeks. The nearby moon Galatea was quickly recognized as playing a major role in confining the arcs via a corotation resonance (Goldreich et al. 1986, Porco 1991). However, the Goldreich et al. (1986) corotation-sites are in fact unstable when solar radiation forces on dust are taken into account (Foryta and Sicardy 1996). Thus the dust in the arcs must be replenished by macroscopic source particles. This however poses a new problem, since mutual impacts between macroscopic arc particles will rapidly de-stabilize their confinement (Hanninen and Porco 1997). In Salo and Hanninen (1998) they show that large particles in corotation sites can be stabilized on non-colliding orbits by their mutual self gravity. Moreover, such particles could act as a source of dust, and also could confine dust arcs spanning over several corotation sites. Observationally one signature would be the clumpy substructure of the arcs due to possible presence of sub-km particles. Several analogues to the Neptune ring arcs have now been found in the Saturn system (Hedman et al. 2007, 2009, Ferrari and Brahic, 1997). Again, this intensifies the interest in Neptune's ring arcs for the purpose of comparative studies.

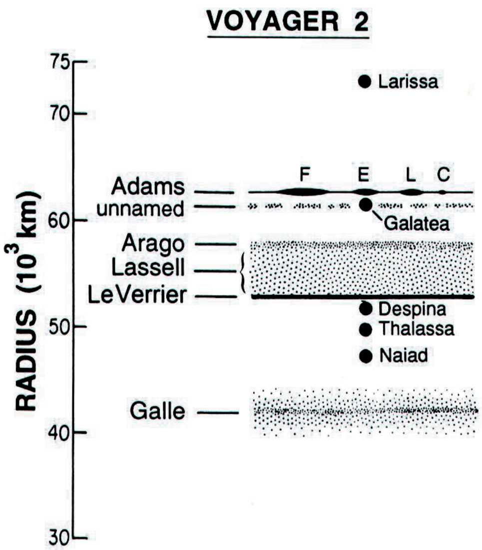

Fig. 1. Neptune's rings feature broad rings, narrow rings and arcs, from Porco et al., 1995.

Neptune Rings and Inner Satellites: Key Science Questions and Measurement Objectives

1. What is the *current configuration of the rings, dust disk, and ring arcs* and how has that configuration evolved since the Voyager flyby in 1989? Post-Voyager observations of the ring arcs (Sicardy et al. 1999, Dumas et al. 1999, de Pater et al. 2005) throw at least the details of the standard resonance explanation into some doubt, making it all the more imperative to obtain new observations to understand this mysterious system. The arcs fell 20° behind their predicted location and definitively outside the resonance. The leading arcs have also shifted forward and decreased in brightness relative to the others. The trailing arc, Fraternité, is the most stable and seems to track at the exact resonance rate. The other arcs continue to evolve, with the leading arcs Courage and Liberté now almost completely gone. The narrow Le Verrier ring, interior to the Adams ring, has also brightened by a factor of four since Voyager (Showalter et al. 2005, de Pater et al, 2005). High-resolution observations by Argo may help resolve the mechanisms behind these changes. Understanding the evolution of the configuration of the ring-satellite system will constrain models of the long-term evolution and the origin of the ring system.

2. What is the *composition of the rings and inner satellites*? The composition of planetary rings in general remains a major unknown, beyond some zero-order understanding. Saturn's rings are dominated by water ice, but their pinkish color - not dissimilar from Triton at visual wavelengths - calls for at least one important secondary component. We are ignorant of Neptune's ring composition or how it varies with location, except that the material seems to be dark. The compositional diversity of solid objects in the outer solar system is apparent from the near-infrared spectra of bodies such as Triton, Pluto and Charon, which show absorption features of varying strengths due to varying amounts of methane, water and other ices on their surfaces. The smaller moons and rings of Neptune might have originally been made of the same stuff as these larger objects, but they also would have had much different evolutionary histories (perhaps less thermal processing, more pollution from infalling matter, etc.). Comparing the surface composition of these smaller objects to their larger neighbors should therefore help clarify both of their origins and histories, but it is difficult to obtain good-quality spectra of these very small and/or faint objects from ground-based observatories.

3. What are the *particle size distributions* in the rings and ring arcs? Do larger parent bodies populate and/or confine the ring arcs? From Voyager and ground-based observations we have very little information on the particle-size distribution of Neptune's rings and arcs. Most of them contain a significant fraction of dust, but the particle sizes and distribution of larger parent bodies is not known. Because dust lifetimes are short, identifying the full size distribution is critical to understanding the timescales for ring evolution. The combination of phase coverage from a flyby with the vastly improved capability of a modern imaging system will allow us to measure the phase curve in the visual and near-IR.

4. What *dynamical processes* are responsible for ring structure? Goldreich et al. (1986) predicted that the widths of arcs confined by the corotation sites should oscillate with orbital longitude. Because slant optical depths of the arcs are not small, changes in radial width should map into changes in integrated reflectivity. The Voyager flyby was too rapid, and its longitude coverage too incomplete, to show such changes.

5. What is the *relationship between the rings and small satellites*? Do satellites play a role in confining the ring arcs? At Neptune the small moons and rings are interspersed but only one resonance (Galatea-Adams) has been identified. The narrow Le Verrier ring requires radial confinement, but no mechanism has been proposed; Despina, though nearby, does not show any resonant relationship. Source bodies, possibly large enough to be considered moons, are also expected in or near the dusty Galle, Lassell and Arago rings.

Relative to the other giant planets, Neptune seems to be depleted in small moons. Smith et al. (1989) noted "the relatively large number of big bodies close to Neptune might lead one to expect a proportionately large abundance of small moonlets in that region. Yet, our search for satellites to date does not support the existence of more than two objects…with diameters less than 100 km." Karkoschka (2003) re-examined the Voyager data but found no additional moons. Perhaps some mechanism truncates the size distribution, maybe by disrupting smaller bodies or accreting them onto larger moons.

6. Do *expansive dust rings* exist around Neptune? All of the other ring systems are known to be circumscribed by expansive, faint rings of dust—the "gossamer" rings at Jupiter, Saturn's G and E rings, and the μ and ν rings (R/2003 U 1 and R/2003 U 2) of Uranus (Showalter and Lissauer 2006). Reasoning purely by analogy, a search for the outermost and faintest rings of Neptune is justified. Such rings are interesting because they show the influence of non-gravitational perturbations that tend to be masked in denser rings. They are also significant for our census, because they require embedded source bodies, in the form of either moons or unseen swarms of tinier moonlets. Thus, this search could plausibly reveal the presence of bodies that are too small to be seen directly.

Table 1. Ring Science Questions to be addressed by Argo.

Neptune Level 1 Ring Science Objectives	**Data Required**	**Instrument(s)**
1. What is the *current configuration of the rings, dust disk, and ring arcs* and how has that configuration evolved since the Voyager flyby?	High resolution images at low and high phase angles	Narrow angle camera
2. What is the *composition of the rings and inner satellites*?	Color images and Near IR spectra	Narrow angle camera, Near IR spectrometer
3. What are the *particle size distributions* in the rings and ring arcs? Do larger parent bodies populate and/or confine the ring arcs?	Visible and near IR images at a variety of phase angles	Narrow angle camera, Near IR imager
4. What *dynamical processes* are responsible for ring structure?	Movies	Narrow angle camera
5. What is the *relationship between the rings and small satellites*? Do satellites play a role in confining the ring arcs?	High resolution images	Narrow angle camera
6. Do *expansive dust rings* exist around Neptune?	High and low phase images	Wide angle cameras

III. Mission Description

Here we address just a few key aspects of the Argo mission concept. The most important question is “what are the opportunities to get to Neptune, and what are the characteristics of the trajectory options?” Flight system design must be achievable within the New Frontiers budget.

Trajectories

A window of opportunity to go to Neptune in a relatively short amount of time (8 – 11 years) using gravity assists at Jupiter and Saturn exists from 2015 to 2019, with a few backup launch opportunities in 2020. These trajectories are similar to the tour flown by Voyager, featuring a flyby of Jupiter ~1.5 years after launch, and Saturn flyby ~3 years after launch. (This is not quite the Voyager Grand Tour in that Uranus has moved out of range.) These flybys, besides providing gravity assists, offer opportunities for instrument calibration and science measurements. The path from Saturn to Neptune is largely determined by the choice of the subsequent KBO. A balance of desired Triton viewing geometry and KBO selection determines details of the geometry of the Neptune flyby. Figure 2 shows an example of the type of trajectory and trip time that is available in 2019.

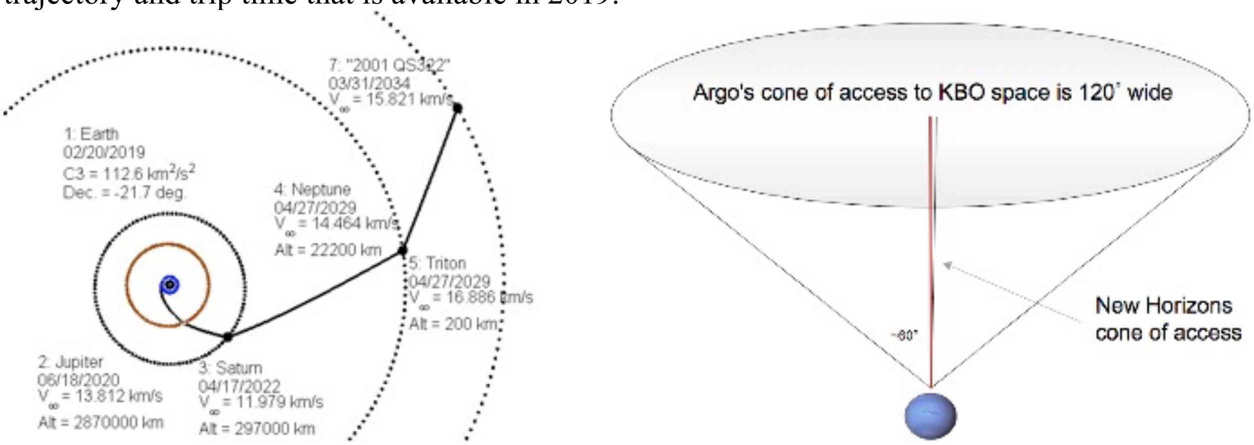

Fig. 2. A. This trajectory features a Jupiter and Saturn gravity assist that result in a flight time to Neptune of 9 years and a KBO flyby 4 years later. B. Argo access to the Kuiper Belt compared with that of New Horizons. Neptune's mass provides a gravity assist that will permit selection of a KBO with the highest scientific interest. Our cone of accessibility includes ~70 of the largest KBOs.

Flight System

The Argo spacecraft would be functionally similar to the New Horizons spacecraft already *en route* to Pluto. Like New Horizons, Argo will need onboard data storage to retain the copious data taken during close encounters, for subsequent relay to Earth. Also like New Horizons, the Argo spacecraft would use a radioisotope power source (RPS) for electric power. That power source could be an MMRTG (scheduled to fly on the MSL mission in 2009) or an Advanced Stirling Radioisotope Generator (ASRG) currently under development by NASA, DOE, and industry partners. An attractive option is to decouple high-gain antenna (HGA) pointing from science-instrument pointing by articulating the HGA via a gimbal, as is currently employed on Mars orbital missions. This affords significantly greater flexibility in scheduling science-data acquisition and downlink periods, with the possibility of doing them simultaneously. For a modest 10 W of RF power out, downlink data rates of 5 to 15 kbps are available depending on HGA diameter. By adhering to a New Horizons spacecraft level of complexity Argo will remain within the New Frontiers budget.

Table 2. Strawman Payload

Instrument	Heritage	Anticipated Capability
High-Resolution Visible	NH LORRI	A narrow angle CCD camera will provide the highest-resolution images of Triton and a KBO, discrete features in Neptune’s atmosphere, and high-phase-angle observations of the rings. Such a camera (far beyond the capabilities of the 1970s-

Imager		era Voyager vidicon) will yield high-resolution high-SNR images over a wavelength range broader than Voyager (the Voyager camera was only sensitive to ~ 600 nm).
Near-infrared Imager	NH Ralph	A near-IR instrument capable of mapping the distribution of surface frosts; this technology did not exist at the time of the Voyager Encounter. Distribution of CH_4, CO and CO_2 ices will address volatile transport on Triton and the KBO.
Ultraviolet Imaging Spectrograph	Reduced Cassini	The ultraviolet instrument will observe stellar and solar occultations to study Triton's and KBO's and Neptune's atmosphere and rings. FUV imaging will be used to map water distribution on the KBO and aurora on Neptune
Thermal Imager	LRO Diviner	Multi-channel infrared filter radiometer, where each channel is defined by a linear, 21-element, thermopile detector array at the telescope focal plane, and its spectral response is defined by a focal plane bandpass filter.
Charged Particle Spectrometer	Messenger FIPS, Cassini CAPS	Measures the flux of ions as a function of mass per charge and the flux of ions and electrons as a function of energy per charge and angle of arrival relative to the instrument for ions in the Neptunian magnetosphere in the vicinity of Triton. Information on composition, density, flow velocity, and temperature of ions and electrons will be derived from the flux measurements. An energy range of a few eV to several tens of keV is desired for both ion and electron measurements.
Magnetometer	ST5	The magnetometer will look for signs of present or past dynamo magnetic field in Triton to try to infer the presence of a liquid ocean through electromagnetic induction studies that use the rotating magnetic field of Neptune as a sounding signal. A similar experiment will be performed at the KBO where the changing IMF field would be used as the primary inducing field.
Plasma Wave Spectrometer (upscope)	Juno	Measures the plasma and radio waves generated in Neptune's magnetosphere and ionosphere of Triton. The wave amplitude would be measured over a frequency of a few Hz to a MHz. The instrument consists of two subsystems, the electric field system which measures the electric field induced in long thin wire probes (3 to enable source location), and a magnetic search coil which is mounted close to the spacecraft. The electric field measurements can provide accurate plasma densities and provide in situ dust impact rates and particle size distributions.

Additional science instruments, such as a Dust Detector, and Radio Science occultation capabilities are highly desirable for enhanced science return but are outside the currently proposed strawman payload.

IV. Summary

Our understanding of the Kuiper Belt – particularly its key role in the early evolution of the Solar System – has revolutionized our understanding of the Solar System as a whole in recent years. Results from Pluto will be coming back from New Horizons (July 2015), well before the Argo launch window. With the addition of Argo data we will have explored just four of a vast population of KBO's.

A mission to the Neptune system is one of the top-ranked missions in the last Planetary Decadal Survey and was discussed in the related community contributions. However, it was deferred to later decades, due in large part to the assumption that a flagship-class orbiter mission was required. This action has far from dampened enthusiasm for, and the recognition of the importance of, such a mission:

1) Triton was explicitly discussed as a top target in the Large Bodies panel of the Decadal Survey
2) A Neptune/Triton mission is one of four named flagship missions in the 2006 Solar System Exploration Roadmap
3) Two different Neptune missions were selected for "Vision Mission" studies in 2004
4) Neptune is named a giant-planet priority in the Outer Planets Pathways document
5) The NRC Committee on Assessing the Solar System Exploration Program's Midterm Report ("Grading NASA's Solar System Exploration Program") specifically recommends

the following: "*The next Solar System exploration decadal survey should address the objectives and merits of a Neptune/Triton mission*".

A mission to Triton/Neptune and beyond to a scientifically-selected KBO can be achieved within New Frontiers resources, yet the depth and breadth of science would be of flagship class and filled will historic "Firsts".

The opportunities for exploration in the distant Solar System are by their very nature limited to *only* the New Frontiers and Flagship classes of mission. Furthermore, no spacecraft will have flown by an ice giant system in two decades, whereas *every other class of object in the Solar System* has had -- or will have -- at least a flyby by 2015, if not multiple flybys and/or orbiters.

For all these reasons, Argo should be considered the top candidate for the New Frontiers 4 selection, to enable the continuing and timely exploration of our "home in space."

References

Charnoz, S., Morbidelli, A., Dones, L., Salmon, J. 2009. Did Saturn's rings form during the Late Heavy Bombardment? *Icarus* **199**, 413-428.

de Pater, I. et al. 2005. The dynamic neptunian ring arcs: Evidence for a gradual disappearance of Liberte and resonant jump of Courage. *Icarus* **174**, 263-272.

Dumas, C., et al. 1999. Stability of Neptune's ring arcs in question. *Nature* **400**, 733–735.

Ferrari, C. and A. Brahic, 1997. Arcs and clumps in Encke division of Saturn's rings, PSS. 45, 1051-1067.

Foryta, D. and B. Sicardy 1996. The Dynamics of Neptunian ADAMS Ring's Arcs. *Icarus* 123, 129-167.

Gomes, R., Levison, H. F., Tsiganis, K., Morbidelli, A. 2005. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* **435**, 466-469.

Goldreich, P., Tremaine, S., and Borderies, N. 1986. Towards a theory for Neptune's arc rings. *Astron. J.* **92**, 490–494.

Hanninen, J. and C. Porco, 1997. Collisional Simulations of Neptune's Ring Arcs. *Icarus* 126, 1-27.

Hedman, M.M. et al. 2007. The source of Saturn's G ring. *Science* **317**, 653-656.

Hedman, M.M. et al. 2009. Three tenuous rings/arcs for three tiny moons. *Icarus* **199**, 378-386.

Hubbard, W. B., et al. 1986. Occultation detection of a Neptunian ring-like arc. *Nature* **319**, 636–640.

Karkoschka, E. 2003. Sizes, shapes, and albedos of the inner satellites of Neptune. *Icarus* **162**, 400–407.

Krimigis, S. M. et al., 1989. Hot plasma and energetic particles in Neptune's magnetosphere. *Science* **246**, 1483-1488.

Morbidelli, A., Levison, H. F., Tsiganis, K., Gomes, R. 2005. Chaotic capture of Jupiter's Trojan asteroids in the early Solar System. *Nature* **435**, 462-465.

Nicholson, P. D., Mosqueira, I. and Matthews, K. 1995. Stellar occultation observations of Neptune's rings: 1984–1988. *Icarus* **113**, 295–330.

Porco, C. C. 1991. An explanation for Neptune's ring arcs. *Science* **253**, 995–1001.

Porco, C. C., et al. 1995. Neptune's ring system, in *Neptune and Triton*, D. P. Cruikshank (Ed.), University of Arizona Press, Tucson, pp. 703-804.

Salo, H. and J. Hanninen, 1998. Neptune's Partial Rings: Action of Galatea on Self-Gravitating Arc Particles. *Science* 282, 1102.

Showalter, M. R., Lissauer, J. J., de Pater, I. 2005. The rings of Neptune and Uranus in the Hubble Space Telescope. *BAAS* **37**, 772.

Showalter, M. R. and Lissauer, J. J. 2006. The second ring-moon system of Uranus: discovery and dynamics. *Science* **311**, 973-977.

Sicardy, B., et al. 1999. Images of Neptune's ring arcs obtained by ground-based telescope. *Nature* **400**, 731–733.

Smith, B. A., et al. 1989. Voyager 2 at Neptune: Imaging Science results. *Science* **246**, 1422–1449.

Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H. F. 2005. Origin of the orbital architecture of the giant planets of the Solar System. *Nature* **435**, 459-461.