Ice Giants – The Return of the Rings

A Science White Paper for the Planetary Science and Astrobiology Decadal Survey 2023-2032

Hsiang-Wen Hsu[1] (sean.hsu@lasp.colorado.edu; +1 720 470 3148)

Co-authors/Endorsers:

Ali Sulaiman[2], Hao Cao[3], Matthew M. Hedman[4], Omakshi Agiwal[5], Nicolas Altobelli[6], Kevin Baillie[7], Tracy M. Becker[8], Michel Blanc[9], Shawn M. Brooks[10], Aurélien Crida[11], Jeffrey N. Cuzzi[12], Imke de Pater[13], Paul Estrada[14], Lina Hadid[15], Mihály Horányi[1], Gregory J. Hunt[5], Wing-Huen Ip[16], Nozair Khawaja[17], Sascha Kempf[1], Peter Kollmann[18], William S. Kurth[2], Erin J. Leonard[10], Simon Linti[17], Christopher R. Mankovich[19], Kelly E. Miller[8], Luke Moore[20], Michiko Morooka[21], James O'Donoghue[22], Mark E. Perry[18], Frank Postberg[17], Elias Roussos[23], Daniel Schirdewahn[24], Jürgen Schmidt[25], Oleg Shebanits[5], Mark Showalter[14], Frank Spahn[24], Linda Spilker[10], Tom Spilker[26], Ralf Srama[27], Jamey R. Szalay[28], Wei-Ling Tseng[29], J. Hunter Waite Jr.[8]

[1]University of Colorado Boulder, USA; [2]University of Iowa, USA; [3]Harvard University, USA; [4]University of Idaho, USA; [5]Imperial College London, UK; [6]European Space Agency; [7]IMCCE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC University Paris 06, Université Lille, France; [8]Southwest Research Institute, USA; [9]IRAP, CNRS-Université Toulouse III, France; [10]JPL, California Institute of Technology, USA; [11]Université Côte d'Azur, Observatoire de la Côte d'Azur, Lagrange (UMR7293), France; [12]Ames Research Center, NASA, USA; [13]University of California Berkeley, USA; [14]SETI Institute, USA; [15]LPP, CNRS, École polytechnique, Institut Polytechnique de Paris, Sorbonne Université, France; [16]National Central University, Taiwan; [17]Freie Universität Berlin, Germany; [18]The Johns Hopkins University Applied Physics Laboratory, USA; [19]California Institute of Technology, USA; [20]Boston University, USA; [21]Swedish Institute of Space Physics, Sweden; [22]Japan Aerospace Exploration Agency (JAXA), Japan; [23]Max Planck Institute for Solar System Research, Germany; [24]University of Potsdam, Germany; [25]University of Oulu, Finland; [26]Independent Consultant; [27]Universtität Stuttgart, Germany; [28]Princeton University, USA; [29]National Taiwan Normal University, Taiwan

A portion of this study was supported by the International Space Science Institute, International Team: A New View of Ring-Planet Interactions from Cassini's Grand Finale.

Summary

Here we highlight recent advances in our knowledge about Saturn's ring system and bring forward the outstanding science issues that could be addressed by studying the ring systems of the ice giants. We focus on interactions between planetary rings and other elements in the system, including the moons, host planet, and its magnetosphere, and conclude that ring science investigations, in accordance with magnetospheric and atmospheric science disciplines, are essential in advancing our knowledge of solar system evolution, the origin and evolution of the moons and Ocean Worlds, as well as contemporary phenomena observed in the ice giant systems. We request that the study of ice giant ring systems to be considered a top priority for all future ice giant explorations.

Introduction

Planetary rings have been an inspiration to star gazers and physicists for centuries (Brahic and Ferrari 1992). Even in the space age, their unique properties make them a cross-disciplinary research field with broad implications (see also recent book Planetary Ring Systems edited by Tiscareno and Murray, 2018). Among the ringed giant planets in the solar system, Saturn's rings demonstrate the magnificence and complexity of a ring system, even resembling distant cosmic discs (Burns and Cuzzi, 2006; Cuzzi et al., 2010). Fluid-like, collective behavior of ring particles dominates the appearance and the dynamical evolution of dense rings through collisions and gravitational interactions with the moons, embedded or in resonance, as well as the host planet (e.g., Brahic 1977; Brahic and Ferrari 1992, Sremčević et al.; 2007; Hedman and Nicholson 2013; Spahn et al., 2018). The broad span of the rings allows them to serve as a witness plate to examine the endogenous and exogenous processes altering the composition of the system and informing about their origin (Ip 1983b; Cuzzi and Estrada, 1998). Diffuse rings with various colors and flavors are supplied by different mechanisms that tell the stories about their source moons (Hedman et al., 2007, 2009, 2011; Sun et al., 2017), including Enceladus, the only known Ocean World that constantly emits vapor and icy grains from its subsurface ocean forming Saturn's unique E ring (Spahn et al., 2006; Waite et al., 2006; Postberg et al., 2011; Iess et al., 2014; Khawaja et al., 2019).

Thanks to the 13-year comprehensive study by the NASA-ESA Cassini-Huygens mission as well as advances in numerical simulation techniques, our understanding of Saturn's rings and their role in the system has been greatly improved. One of the most important aspects now realized is that **the evolution of the planetary rings and its moon system are strongly coupled through gravitational interactions** (e.g., Charnoz et al., 2018 and references therein). The migration of the moons left marks in the rings though resonances with ring particles. Simultaneously, angular momentum is transferred from the rings to drive the moons' outward migration. The sign of a moon formed by self-gravity at the outer edge of the ring outside Saturn's Roche zone has been observed (Murray et al., 2014), supporting the idea of a co-evolutionary ring-moon system. **The rings and moons of a giant planet system are essentially the two sides of the same coin and cannot be studied separately** (Charnoz et al., 2010; Canup 2010; Crida and Charnoz, 2012; Neveu and Rhoden, 2019). Towards the edge of the planet, the Cassini Grand Finale mission brought the spacecraft in between the inner edge of the rings and Saturn's cloud tops for the first time (Altobelli 2017), revealing a wealth of new information about the rings and moons, and how the rings interact with Saturn's upper atmosphere and magnetosphere through the infalling ring material (Dougherty et al., 2018; Hsu et al., 2018; Mitchell et al., 2018; Roussos et al., 2018; Waite et al., 2018; Buratti et al., 2019; Iess et al., 2019; Tiscareno et al., 2019).

Scientific and operational lessons learned by Cassini at Saturn can be readily applied to study the ice giants' ring-moon systems. It is also important to think about how the ring-moon-planet evolution of each individual planet fits into a global picture of solar system evolution (e.g., Charnoz et al., 2009; Hedman 2015), and how planetary systems evolve in general. The goal of this white paper is to emphasize the essential role the planetary ring-moon system in our understanding of the formation and evolution of planetary systems. In the following we discuss two science topics focusing on the ring system of Saturn, to highlight what has been learned and the implications regarding the study of the ring systems around ice giants. The discussion then expands to three fundamental, outstanding questions that can be addressed by studying the ring-moon-planet interactions at the ice giants.

Old vs. Young Rings of Saturn

A major question regarding planetary ring systems is how and when they formed. There has been a long-standing debate as to whether Saturn's rings are a primordial part of the Saturn system or if they were added to Saturn in the geologically recent past. There are multiple arguments for and against either of these options (see Charnoz et al., 2018; Crida et al., 2019; and Estrada et al. 2019 and references therein), but in general **the arguments for why the rings should be primordial emerge from considerations of how the rings could have formed, while many of the arguments for why the rings should be young emerge from considerations of the rings' present properties.**

New data from Cassini's Grand Finale appear to support the idea that Saturn's rings are much younger than the solar system. It has long been known that Saturn's rings are composed of relatively pure water ice (Kuiper and Cruikshank, 1970). This is surprising because other solid objects in the outer solar system have large fractions of other materials, such as organics and silicates. While the rings could have formed with a different initial composition, comets constantly strike the rings and so a pure ice composition should not persist. Indeed, Cassini measurements of the ring's mass (Iess et al., 2019) and the current impact flux (Kempf et al., 2017) indicate that less than 100 million years' worth of interplanetary debris has been mixed into the rings. At the same time, in-situ measurements found surprisingly high fluxes of material flowing out of the rings into the planet (Hsu et al., 2018; Perry et al., 2018; Waite et al., 2018). If this material continued to flow into Saturn at these rates, the rings would lose a significant fraction of their total mass over 100 million years (O'Donoghue et al., 2013, 2019). These comparable timescales could suggest that Saturn's rings may only be around 100 million years old (there is also dynamical evidence that something might have happened to the moon system around this long ago, see Ćuk et al. 2016).

While the above evidence is suggestive, it is not ironclad and it does not provide a complete picture of the rings' origins or history. Specifically, it is not at all clear how the rings could have formed so recently. The formation of the rings necessarily involves moving material close to the planet, which is the same process that creates impacts on solid bodies. However, the cratering records indicate that such events are much more likely to happen early in the solar system's history, so why would such an event have occurred at Saturn so recently? One way to solve this problem is to reconcile the above measurements with primordial rings. For example, the material flowing out of the rings seems to have a lower water fraction than the rings themselves, so perhaps the rings are somehow maintaining their pure ice composition through some still-unidentified mechanism. Alternatively, one could consider more complex models of how ring-moon systems evolve. For example, the present rings could just be the remnants of a much more massive ring system that existed earlier. Such possibilities are currently being investigated (Crida et al. 2019), but it is not yet clear whether any of these options are fully consistent with all the observations.

More generally, recent work has shown that the long-term evolution of ring-moon systems can be much more complex than previously thought. For example, the material surrounding Mars, Uranus and Neptune can potentially cycle back and forth between rings and moons multiple times over the last 4.5 billion years (Colwell and Esposito, 1992, 1993). The basic idea is that moons orbiting close to these planets naturally migrate inwards due to tidal interactions with the planet. This eventually brings them close enough to the planet to be pulled apart, forming rings, which will then spread both inwards and outwards, potentially pushing material far enough out to re-form into moons (Hesselbrock and Minton 2017, 2019, Cuk et al. 2020). The ring-moon systems of Uranus and Neptune, as well as the Martian moon Phobos, could therefore represent material in different phases of this cycle. While neither Saturn's nor Jupiter's ring-moon systems are expected to behave in this way, future studies of all these ring systems are likely to clarify their origins and history.

Ring-Planet Interactions at Saturn

O'Donoghue et al. (2013) reported a latitudinal pattern in Saturn's ionospheric H_3^+ emission associated with ring structures as mapped along the magnetic field lines connecting to the rings. Saturn's spin-aligned planetary magnetic field provides a natural coordinate system whereby each segment of the rings is magnetically connected to a unique range of latitudes in the ionosphere of Saturn that is independent of rotation phase. Latitudinal variations of ionospheric properties therefore, to some extent, mirror the rings. This magnetic connection facilitates processes such as electrodynamic coupling and transport of charged particles from the rings to Saturn (Northrop and Hill; 1982, Ip 1983a; Connerney 1986). This so-called "ring rain" effect indicates the alteration of the ionospheric properties by the infalling ring material.

In 2017, the Cassini Grand Finale mission revealed a number of surprises and firmly underlined **Saturn's rings as a multifaceted player in the physical and chemical dynamics of the system**. Some of the highlights about the ring-planet interactions are: (i) Repeated in-situ observations detected ring particles falling into Saturn altering its ionosphere at great depth (Hsu et al., 2018; Mitchell et al., 2018; Perry et al., 2018; O'Donoghue et al.; 2019; Shebanits et al., 2020). (ii) Chemical interactions were discovered between Saturn and its rings from the inclusion of volatile compounds (e.g. methane) to larger organic-bearing nanograins (Waite et al., 2018; Miller et al., 2020). (iii) A large-scale, persistent, electrodynamic coupling between Saturn's ionosphere and the main rings (Sulaiman et al., 2018, 2019; Dougherty et al., 2018) – a diagnostic of the exchange of electromagnetic energy and likely angular momentum between the two.

Why is it essential to study the rings of the ice giants?

The mass loss associated with the ring-planet interactions revealed by the Cassini Grand Finale could have significant effects on the general evolution of planetary ring-moon systems, especially at ice giants, given the extended atmosphere (Broadfoot et al., 1986, Waite et al., 2018) and the higher exogenous dust influx (Poppe et al., 2016) leading to possible stronger erosion. Catastrophic collision events could be more frequent to form debris rings around ice giants. Compared to Saturn, the origin of ice giants' rings is even less understood. However, there is a synergistic opportunity presented by future study of ice giants' ring-moon systems, which will enable new investigations to previously unsolved questions and to uniquely address other prominent issues related to ice giants and solar system evolution, as discussed below.

1. Do the differences between the ring systems reflect their evolution or origin?

The grand tour of Voyager provided an overview of the diversity of planetary rings. Jupiter's relatively faint rings are a mixture of macroscopic and microscopic particles likely generated as impact ejecta from the embedded moons (Burns et al., 1999). The ring systems of Uranus and

Neptune are packed with narrow rings and small satellites much darker than the water-ice-rich rings and moons of Saturn (Smith et al., 1986). In spite of the difference in appearances, the rings and moons are shaped by similar processes and could follow similar evolution pathways depending on the initial and evolutionary conditions. What has yet to be understood is whether **the drastically different ring systems we see today represent a chronological sequence of a unified ring evolution process** (e.g., will Saturn's rings resemble Uranus' in 100s Myr?), **or do the differences largely stem from their independent origin and the chaotic history of the solar system?**

In a way this question is similar to the debate of uniformitarianism versus catastrophism in geology. Our answer to the question could have significant implications not only about our knowledge of the individual ring-moon system (e.g., the old/young ring scenarios of Saturn), but also issues deeply rooted in the understanding of the origin and formation of planetary systems in general. For example, does the formation of planetary rings belong to a hierarchy associated with the planet migration scheme such as the Grand Tack (Walsh et al., 2011)? Does the cratering history recorded on the moons reflect the ring formation event(s) or the extrinsic inputs from heliocentric impactors (Ćuk et al., 2016)? What is the coupling between the evolution of giant planet interiors and the tidal interactions with the associated ring-moon system (Fuller et al., 2016, Lainey et al., 2020)? How are the ring-moon systems affected by the proposed giant impacts leading to the large tilt of Uranus and Neptune (Charnoz et al., 2018)? For instance, the ring-moon system of Neptune likely has been significantly altered by the capture of Triton, a potential Ocean World with a Kuiper-Belt origin that bears its own unique science interests. While it may be more difficult to make direct comparison with the ring-moon system of Saturn, the study of the Neptune system could inform how exogenous influences (e.g., by Kuiper Belt Objects) affect the ring-moon system and why the rings are all prograde (Charnoz et al., 2018), in contrast to the retrograde Triton.

While we have learned and set critical constraints on various hypotheses about the formation of Saturn's ring system (some may argue that it is still not sufficient), there remain fundamental barriers difficult to overcome without a second or third detailed study of another ring-moon system. **The intrinsic differences of the ice giant ring-moon systems offer a unique opportunity to examine the hypotheses and ideas inherited from the study of Saturn's rings and solar system evolution in different physical and compositional regimes that are not possible elsewhere.**

In addition, the detections of rings around exoplanets remain tentative (Kenworthy and Mamajek 2015), but affirmative discoveries of "exo-rings" may only be years away (Barnes and Fortney, 2004) given the fast growth of exoplanet observations. Indications suggest that planetary rings are likely ephemeral, instead of a timeless monument (O'Donoghue et al., 2019; Estrada et al., 2019). Perhaps planetary rings could serve as a chronology tool to date the evolution stage of exoplanet systems, once we have developed an understanding of the ring systems in our solar system.

2. Ocean Worlds – the fellowship of the rings?

Finding an ocean midway towards the outer solar system does not quench the thirst of humankind to search for more. The question is how the intricate dance between the planet and its ring-moon system warms the moon(s) so it can, even just temporarily, host liquid water and sustain energy gradients to drive complex chemistry or even support life (see also Nimmo and Pappalardo, 2014)?

While planetary rings may not be necessary to form Ocean Worlds, **the presence of rings would significantly alter the evolution path of the moon system regardless of ring formation scenarios.** With time, the rings lost material by erosion and moon production, and their gravitational influences diminished (Crida and Charnoz, 2012). At the current stage, the ring-moon interactions at Uranus and Neptune are largely limited to the ring-moons (i.e., moons embedded within or shepherding the rings). Yet major moons located further from the rings likely still bear marks left when the rings were much more massive. **Ice giants' moon systems thus provide valuable insights into the ring-moon-planet interactions in the past.**

Voyager 2 images of Miranda and Ariel, two major moons of Uranus show substantial surface tectonic features indicating recent large-scale resurfacing driven by internal processes (Smith et al., 1986; Hendrix et al., 2018). The similarities between them and the mid-sized icy moons of Saturn, including Enceladus, are ideal for comparative planetology to understand the evolution of icy moons, and how and when Ocean Worlds could form in a ring-system around a giant planet. A Uranus mission needs to arrive by the early 2040s because the unimaged northern high latitudes of the planet and major moons will still be visible before the transition to southern spring in 2049 (see Leonard et al., 2020).

The internal structures of the host planet and the moon, as well as the corresponding ring-moon-planet evolution history are essential in understanding the formation of an Ocean World. Many of these studies rely heavily on numerical simulation to trace the evolution in time (Vance et al., 2007; Crida and Charnoz, 2012; Choblet et al., 2017; Neveu and Rhoden, 2019). **Strategic planning of future explorations is essential to provide as many critical observables as possible.** Gravity science and magnetic field measurements have played a critical role in characterizing the internal structure of giant planets and their moons (Kivelson et al., 2000, Khurana et al., 2011, Iess et al., 2014, Kaspi et al., 2018, Guillot et al., 2018, Iess et al., 2019). Novel methods such as ring seismology (Hedman and Nicholson 2013; Fuller 2014, Mankovich 2020) and Doppler imaging seismology (Gaulme et al., 2011) could provide unique constraints on the deep interior of the host planet, informing modeling of how tidal heating evolves as the planet evolves. Compositional characterization of the rings and moons, as well as the present time exogenous material infall are also informative in understanding the ring-moon system composition evolution, ring contamination and erosion, and the composition of ice giants' upper atmosphere, and perhaps help to address why Saturn's rings are mostly water ice. This characterization can be provided by in situ mass spectroscopy, as well as infrared and microwave observations of the deep atmosphere of the giant planets (de Pater et al., 2016; Orton et al., 2017) and cool rings and moons in the outer solar system (Le Gall et al., 2017; Molter et al., 2019; Zhang et al., 2019).

3. What are the rings' effects on the atmosphere / ionosphere / magnetosphere in the ice giant systems?

The rings of Uranus and Neptune take the form of narrow ringlets and broadly distributed dust. The ring system at Uranus exhibits a modest level of complexity relative to the more extensive ring system at Saturn and the relatively simple ring system at Neptune. As we have learned at Saturn, not only do the rings interact gravitationally with the central planet and the moons, they also feed the magnetosphere, exchange materials with the ionosphere and atmosphere, leading to a co-evolving system of atmosphere, ionosphere, rings, and magnetosphere.

Uranus and Neptune both have a hydrogen-helium rich atmosphere, with a measured enrichment in carbon about 100 times the proto-solar value (Atreya et al. 2020). Both the rings and the atmosphere can be shaped by the material transport in between. Material influx from the rings, charged dust in particular, could alter key properties of the ionosphere (Shebanits et al. 2020) which controls the efficiency of ionosphere-magnetosphere coupling and the amount of Joule heating in the middle and upper atmosphere. The middle and upper atmospheres of all giant planets in the solar system suffer a certain amount of "energy crisis" in which unidentified processes are keeping them much hotter than expected from solar insolation alone. The material influx from the rings could be an important piece of this puzzle. It could further alter the chemistry of the atmospheres of Uranus and Neptune through ion-neutral interactions, which in turn would impact the bulk composition, condensation, mixing and circulation of the atmosphere. **Thus, measuring and understanding the composition and rate of material exchange between the rings and the atmospheres of the ice giants is not only important to understand the evolution of the rings and the ionosphere-magnetosphere coupling, but also our inference of the bulk atmospheric composition and the formation scenarios of the ice giants.**

In Uranus' magnetosphere, in contrast to many other dusty rings showing a red spectral slope (de Pater et al., 2006), the μ ring exhibits a distinct blue spectral slope similar to Saturn's E ring which is sustained by Enceladus. Given the importance of the E ring (ultimately Enceladus) as source of neutrals and ions for the magnetosphere of Saturn, **one naturally wonders whether the rings of Uranus (μ ring in particular) and Neptune are important sources of material for their magnetospheres**. Uranus and Neptune possess unique magnetospheres in at least two aspects: strongly tilted and non-dipolar planetary magnetic fields in combination with fast planetary rotation; strongly supersonic solar wind with Alfvén Mach numbers greater than ten (see Kollmann et al., 2020). These lead to magnetospheres that undergo rapid reconfiguration on diurnal timescales. The magnetic equators of Uranus and Neptune, if those can be clearly defined at the radial distance ranges of the rings, would strongly mis-align with the rings unlike the parallel configuration of Saturn's rings and magnetic equator. **This complex geometry poses new questions about the nature of electromagnetic coupling and the routes of material transport between the rings and the upper atmosphere/ionosphere at Uranus and Neptune**. Can large-scale electric current system be maintained between Uranus/Neptune and their rings (Sulaiman et al., 2019)? Can plasma cavity develop along the magnetic field lines connecting the rings and the planet (Farrell et al., 2018)? Can charged dust keep flowing along complex twisted magnetic field lines (Hsu et al., 2018)?

Conclusion

Considering the intrinsic differences, a comprehensive study of ice giants' ring-moon systems and the corresponding interactions should be recognized as an essential goal in advancing our understanding about the formation and evolution of the solar system in the next decade, strategically building upon the legacy of the Voyager, Galileo, and Cassini missions. Future ice giant missions will be able to address critical issues regarding ring-planet interactions, ring-moon composition, and to probe the internal structure of the planet and its moons. Studies of ice giant ring systems should be considered a top priority for all future ice giant explorations.

Reference

Altobelli, N., 2017, *Nature Astronomy*, 1, 560.
Atreya, S.K. et al., 2020, *SSR*, 216:18.
Barnes, J.W. and Fortney, J.J., 2004, ApJ, 616:1193.
Brahic, A., et al., 1977, *AA*, 54, 895.
Brahic, A. and Ferrari, C., 1992, *IAU Symposium*, 152.
Broadfoot, A.L. et al., 1986, *Science*, 233, 4759, 74.
Buratti, B. et al., 2019, *Science*, 364, 1053.
Burns, J.A. et al., 1999, *Science*, 284, 1146.
Burns, J.A. and Cuzzi, J., 2006, *Science*, 312, 1753.
Canup, R.M., 2010, *Nature*, 468, 943-946.
Charnoz, S., et al., 2009, *Icarus*, 199, 413-428.
Charnoz, S., et al., 2010, *Nature*, 465, 752.
Charnoz, S., et al., 2018, In *Planetary Ring Systems*. Cambridge U. Press. 517–538.
Choblet, G. et al., 2017, *Nature Astronomy*, 1, 841.

Colwell, J.E. and Esposito, L.W., 1992, *JGR*, 97(E6):10227-10241.
Colwell, J.E. and Esposito, L.W., 1993, *JGR*, 98(E4):7387-7401.
Connerney, J.E.P. 1986, *GRL*, 13, 773.
Crida, A. and Charnoz, S., 2012, *Science*, 338, 1196.
Crida, A. et al., 2019, *Nature Astronomy*, **3**, 967.
Ćuk, M. et al., 2016, *ApJ*, 820:97.
Ćuk, M. et al., 2020, *APJL*, 2020, 896, L28.
Cuzzi, J. and Estrada, P.R. 1998, *Icarus*, 132, 1.
Cuzzi, J. et al. 2010, *Science*, 327, 1470.
de Pater, I. et al., 2006, *Science*, 312, 92.
de Pater, I. et al., 2016, *Science*, 352, 6290.
Dougherty, M. K. et al. 2018, *Science*, 362, 46.
Estrada, P. et al., 2019, *LPSC abstract* No. 2132.
Farrell, W.M. et al., 2018, *GRL*, 45, 8104-8110.
Fuller, J., 2014, *Icarus*, 242, 283-296.
Fuller, J. 2016, *MNRAS*, 458, 3867-3897.
Gaulme, P. et al., 2011, *AA*, 531, A104.
Guillot, T. et al., 2018, *Nature*, 555, 227-230.
Hedman, M.M., et al., 2007, *Science*, 317, 653.
Hedman, M.M. et al., 2009, *Icarus*, 199, 378.
Hedman, M.M. et al., 2011, *Icarus*, 215, 695.
Hedman, M.M. and Nicholson, P.D., 2013. *AJ*, 146:12.
Hedman, M.M., 2015, *APJL*, 801:L33.
Hendrix, A. et al., 2018, *Astrobiology*, 19, 1.
Hesselbrock, A. J. and Minton, D. A., 2017, AAS/DPS Meeting Abstracts #49.
Hesselbrock, A. J. and Minton, D. A., 2019, *AJ*, 157:30.
Hsu, H.-W. et al., 2018, *Science*, 362, 49.
Iess, L., et al., 2014, *Science*, 344, 78-80.
Iess, L., et al., 2019, *Science*, 364, 1052.
Ip, W.-H. 1983a, *J. Geophys. Res.*, 88, 819-822.
Ip, W.-H. 1983b, *Icarus*, 54, 253-262.
Kaspi, Y. et al., 2018, *Nature*, 555, 223-226.
Kempf, S. et al., 2017, AGU P34A-05
Kenworthy, M.A. and Mamajek, E.E., 2015, *APJ*, 800, 126.
Khawaja, N. et al., 2019, *MNRAS*, 489, 5231-5243.
Khurana K.K. et al., 2011, *Science*, 332, 1186.
Kivelson, M. et al., 2000, *Science*, 289, 1340.
Kollmann, P. et al., 2020. Planetary Science and Astrobiology Decadal Survey White Paper.
Kupier, G.P. and Cruikshank, D.P., 1970, *Sky Telescope*, 39, 14.
Le Gall, A., et al., 2017, *Nature Astronomy*.
Lainey, V. et al., 2020, Nature Astronomy.
Leonard et al., 2020. Planetary Science and Astrobiology Decadal Survey White Paper.
Mankovich, C. R., 2020, *AGU Advances*, 1, e2019VA000142.
Miller, K. et al., 2020, *Icarus*, 339, 113595.
Mitchell, D. G. et al., 2018, *Science*, 362, 50.
Molter, E.M. et al., 2019, *AJ*, 158:47.
Murray C.D. et al., 2014, *Icarus*, 236, 165-168.
Neveu, M. and Rhoden, A.R., *Nature Astronomy*, 3, 543-552.
Nimmo, F. and Pappalardo, R.T., 2016, *JGR*, 121, 1378-1399.
Northrop, T. and Hill, J.R. 1982, *JGR*, 87, 6045-6051.
O'Donoghue, J. et al. 2013, *Nature*, 496, 193.
O'Donoghue, J. et al. 2019, *Icarus*, 322, 251.
Orton, G.S. et al., 2017, *GRL*, 44, 4607-4614.
Perry, M. et al., 2018, *GRL*, 45, 19.
Poppe, A.R. et al., 2016, *Icarus*, 264, 369-386.
Postberg, F., et al., 2011, *Nature*, 474, 620-622.
Roussos, E. and Kollmann, P. et al., 2018, *Science*, 47.
Shebanits, O. et al., 2020, *Sci. Rep.*, 10, 7932.
Smith, B.A. et al., 1986, *Science*, 233, 43-64.
Spahn, F. et al., 2006, *Sci*ence, 311, 1416.
Spahn, F. et al., 2018, In *Planetary Ring Systems*. Cambridge U. Press. 157–197.
Sremčević, M., et al., 2007, *Nature*, 449, 1019.
Sulaiman, A. H. et al. 2018, *GRL*, 45, 14.
Sulaiman, A. H. et al. 2019, *GRL*, 46, 13.
Sun K.-L., et al., 2017, *Icarus*, 284, 206-215.
Tiscareno, M.S. et al., 2019, *Science*, 364, 1054.
Vance, S. et al., 2007, *Astrobiology*, 7, 6.
Waite, J. H., et al., 2006, *Science*, 311, 1419.
Waite, J. H., et al., 2018, *Science*, 362, 51.
Walsh, K.J. et al., 2011, *Nature*, 475, 206-209.
Zhang, Z. et al., 2019, *Icarus*, 317, 518-548.