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Observing Planetary Rings and Small Satellites with the *James Webb Space Telescope*: Science Justification and Observation Requirements

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Abstract

The *James Webb Space Telescope* (*JWST*) will provide unprecedented opportunities to observe the rings and small satellites in our Solar System, accomplishing three primary objectives: (1) discovering new rings and moons, (2) unprecedented spectroscopy, and (3) time-domain observations. We give details on these science objectives and describe requirements that *JWST* must fulfill in order to accomplish the science objectives.

Key words: methods: observational – planets and satellites: general – planets and satellites: rings – telescopes

Online material: color figures

1. Introduction

The rings that adorn the four giant planets are of prime importance as accessible natural laboratories for disk processes, as clues to the origin and evolution of planetary systems and as shapers as well as detectors of their planetary environments (Tiscareno 2013; Hedman 2015). The retinue of small moons accompanying all known ring systems are intimately connected as both sources and products, as well as shepherds and perturbers, of the rings. Leading sources of data on ring systems include spacecraft such as *Cassini* and *Voyager*, but also space telescopes such as *Hubble* (*HST*) and *Spitzer*, as well as ground-based telescopes.

Additionally, the newly discovered rings around the minor planet Chariklo (Braga-Ribas et al. 2014) confirm for the first time that small objects and solid objects can host rings. Due to several similarities with the known giant-planet rings (e.g., orbit rate, radial structure), more detailed observations of the Chariklo rings are likely to shed light on the general workings of ring systems (Tiscareno 2014b). Furthermore, the discovery of the Chariklo rings—along with possible rings around Chiron (Ruprecht et al. 2015; Ortiz et al. 2015)—raises the question of whether rings can also be observed around other minor planets.

The *James Webb Space Telescope* (*JWST*) is being prepared for launch in 2018 to begin a planned five-year mission. *JWST* will have the capability to observe Solar System objects as close as Mars (Milam et al. 2016). Although most of the hardware is already designed and under construction, if not completed, work continues on the development of operations guidelines and software and the completion of calibration tasks. The purpose of this paper is to identify observations of planetary rings that might be undertaken by *JWST* and to describe what is required for *JWST* to accomplish those goals.

The three primary motivations for observing rings and small moons with *JWST* are (1) discovering new rings and moons, (2) unprecedented spectroscopy, and (3) time-domain observations. Section 2 gives details on these science objectives. Section 3 describes requirements that *JWST* must fulfill in order to accomplish the science objectives, and Section 4 gives our conclusions.

2. Observation Types

2.1. Imaging of Faint Objects

In the context of rings, observations of faint targets are complicated by the nearby presence of the bright planet. Strategies are needed to enhance the apparent brightness of

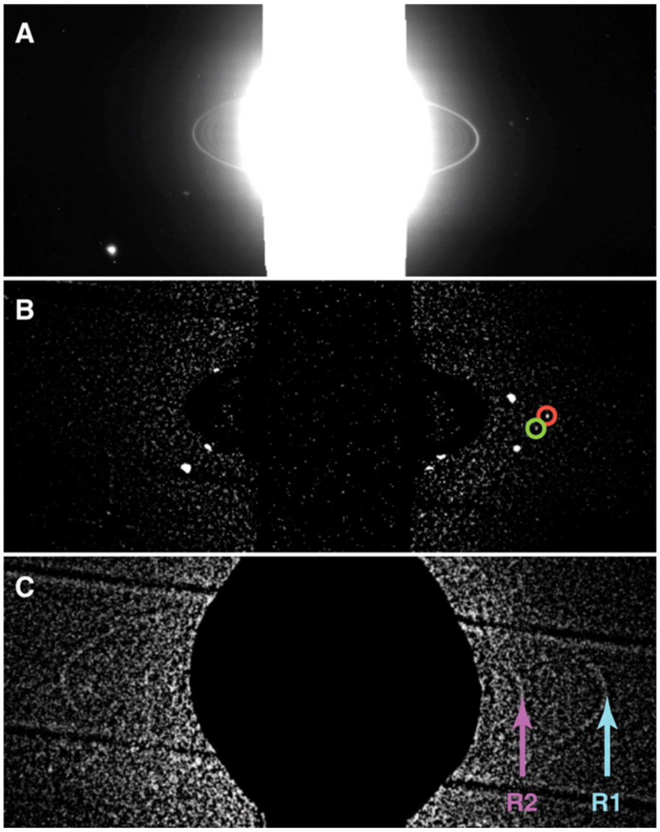

Figure 1. Faint rings and moons of Uranus were discovered by *Hubble* in these 2003 images. (A) Unprocessed image. (B) Filtered image showing two discoveries: Perdita (red circle), recovered 14 years after its discovery by *Voyager*, and Cupid (green circle), observed for the first time. (C) Summation of 24 images showing the newly discovered rings R1 and R2, now respectively named the μ and ν rings. Figure from Showalter & Lissauer (2006).

(A color version of this figure is available in the online journal.)

desired targets and/or to suppress the apparent brightness of the planet (Figure 1).

JWST will be equipped with filters (see Section 3.2; Milam et al. 2016) that allow it to image giant-planet systems at wavelength bands in which the planet is greatly darkened by absorption due to methane and other atmospheric constituents. For observations of faint moons or rings that are close to bright giant planets, this will lead to greatly improved signal to noise and spatial resolution compared to *HST* and other observatories operating in the same wavelength bands (put another way, *JWST* will operate within the infrared methane bands at a spatial resolution comparable to that at which *HST* operates in visible bands, with vastly improved signal to noise when suppression of glare from the planet is an important factor).

As a result, *JWST* will provide major advances in resolving and separating the main rings of Uranus and Neptune, improving upon *HST* and ground-based observations of their fine structure (de Pater et al. 2005, 2006, 2007; Showalter & Lissauer 2006). For example, the faintest moon of Neptune, discovered using *Hubble* in 2013, has a *V* magnitude of 26.5 (Showalter et al. 2013), corresponding to a diameter of 16–20 km if its albedo is 0.07–0.1, as is typical for Neptune's inner moons. While the actual scattered-light contribution for *JWST* is not known, simple scaling would suggest that at the shortest photometric wavelength ($\sim$0.7 μm), *JWST* is $\sim$2 orders of magnitude more sensitive than *Hubble*. At Neptune, this would correspond to discovering moons as small as 2 km across. For targets that are closer and/or brighter, the size may be even smaller.

JWST will have new sensitivity to yet-undiscovered small moons or faint rings, including the predicted rings of Mars (Showalter et al. 2006) and Pluto (Steffl & Stern 2007). The *New Horizons* spacecraft, whose flyby of Pluto will pre-date *JWST*, will likely not have the last word on Pluto's possible rings due to its flyby speed and limited range of viewing geometries. *JWST* will be ideal for follow-up observations, possibly with greater sensitivity, and can also search for rings around other trans-Neptunian dwarf planets.

Imaging of faint objects with *JWST* may be further enhanced by coronagraphy (see Section 3.3).

2.2. *Spectroscopy of Faint Objects*

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 (de Bergh et al. 2013). 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 the origins and histories of both, but it is difficult to obtain good-quality spectra of these very small and/or faint objects from ground-based observatories.

With its large mirror and high-quality spectrometer (Milam et al. 2016), *JWST* will be able to take spectra of very faint objects. Potential targets include the rings and small moons of Uranus and Neptune, which have never been the subjects of a high-fidelity spectroscopic study, as *Voyager 2* did not carry a spectrometer capable of detecting them. Characterizing their chemical compositions is of considerable interest for addressing the origins of the Uranus and Neptune systems as well as for addressing the question of why the Uranian and Neptunian rings are so qualitatively different from those of Saturn (Tiscareno et al. 2013).

By the same token, *JWST* will be able to acquire very sensitive spectra of all objects over a broad range of wavelengths. It will be able to fill in the gap between *Cassini* VIMS and *Cassini* CIRS (from 5 to 8 μm) and will be able to map Saturn's rings in the 1.65 μm water absorption feature, which falls in an internal gap in VIMS' spectral coverage and is unusual in that its depth is useful for mapping temperature variations (Grundy et al. 1999). Its spatial resolution will be a few hundred kilometers, comparable to CIRS, and its sensitivity will be greater, so it should be capable of improving current maps of Saturn's rings in the thermal infrared (though over a very limited range of phase angles) and may achieve the first detection of the faint silicate absorption features at $\gtrsim 10\,\mu$m (Crovisier et al. 1997; Stansberry et al. 2004; Emery et al. 2006), yielding information about the little-understood non-water-ice components of Jupiter's and Saturn's rings.

What we do know about the spectra of giant-planet rings, as they are likely to be seen by *JWST*, is shown in Figure 2. Only Saturn's rings have detailed spectra at low phase angles, taken by *Cassini* VIMS (Hedman et al. 2013). The best spectra to date of Uranus's rings were taken by the Keck telescope in Hawaii (de Kleer et al. 2013), but they are very noisy and should be significantly improved upon by *JWST*. Important advances from *JWST* spectroscopy can also be expected for Neptune's rings and Jupiter's rings, as no spectra of quality have been taken of either system at low phase angles. Galileo NIMS took spectra of Jupiter's rings at very high phase angles (e.g., Brooks et al. 2004), but these are dominated by diffraction and do not indicate the spectral features that *JWST* would see. Also shown in Figure 2 is a phase curve for Jupiter's rings (Porco et al. 2003), which indicates that the observed brightness as a ratio of the solar flux when the rings are seen face-on (that is, the normal I/F) is near 5×10^{-7} at zero phase. Since *JWST* will always see Jupiter's rings nearly edge-on, the observed flux will be some $10\times$ to $100\times$ brighter than that.

Spectroscopy of faint objects out to 5 μm with *JWST* may be further enhanced by coronagraphy (see Section 3.3).

2.3. Time-domain Science

Time-domain observations (sustained observation and tracking) of targets that are faint, recently discovered, or known to be changing are of high importance. *JWST* observations will be important for continuing to characterize the chaotic orbits of moons including those of Pluto (Showalter & Hamilton 2015), Prometheus and Pandora at Saturn (Goldreich & Rappaport 2003) and Mab at Uranus (Kumar et al. 2015), as well as the evolving ring arcs of Neptune (de Pater et al. 2005; see also Figure 3), progressively winding ripple patterns in the rings of Jupiter and Saturn that trace cometary impacts (Hedman et al. 2011; Showalter et al. 2011), and other faint targets. It may also be capable of tracking the azimuthal arcs or clumps in the rings of Jupiter (Showalter et al. 2007) and the

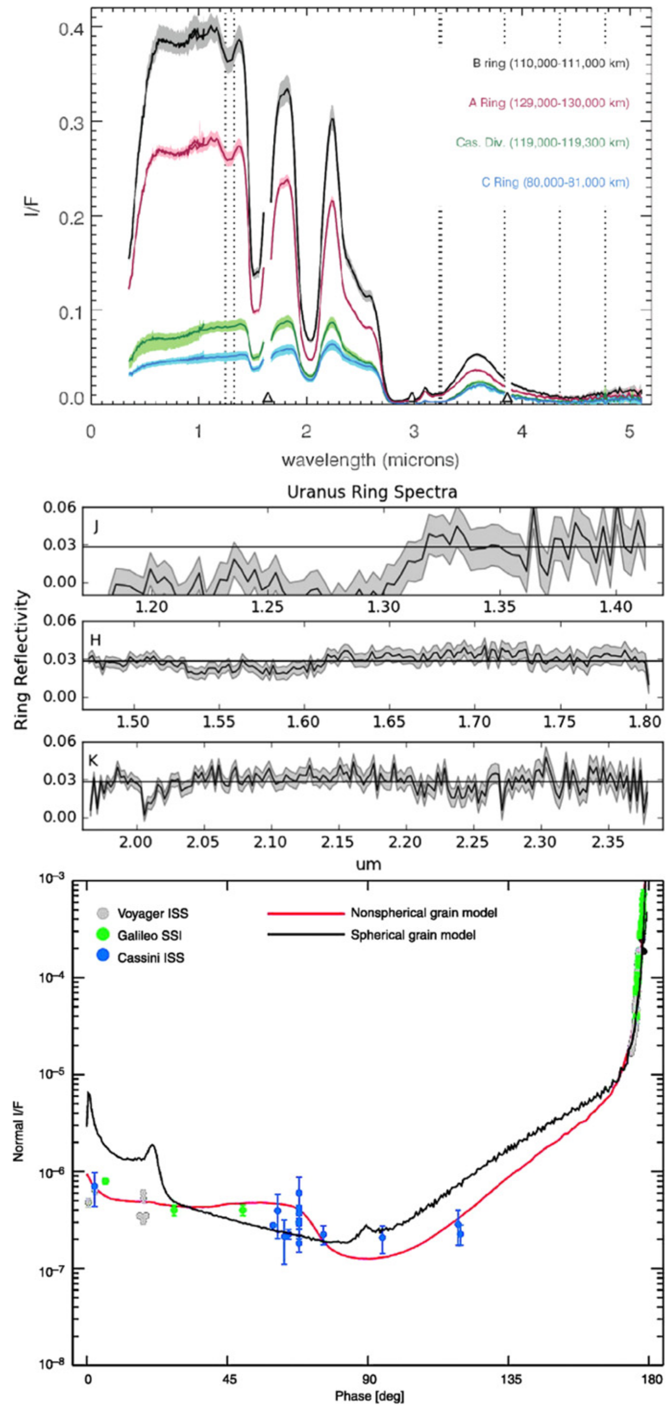

Figure 2. (Top) Average *Cassini* VIMS spectra of the lit face of selected regions in Saturn's main rings (color-coding described in the panel) at low phase angles; from Hedman et al. (2013). (Middle) Keck spectra of Uranus's main rings; from de Kleer et al. (2013). (Bottom) The brightness of Jupiter's main ring at visible wavelengths as a function of phase angle; from Porco et al. (2003).

(A color version of this figure is available in the online journal.)

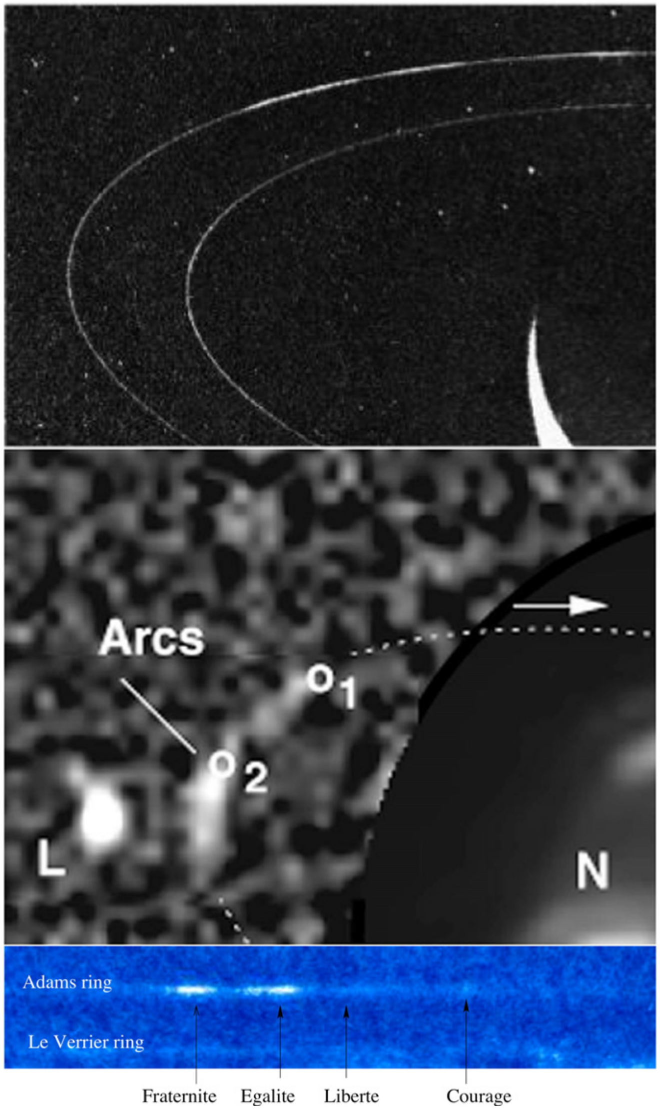

Figure 3. The ring arcs of Neptune were first imaged by *Voyager* (top), then reacquired in 1996 and beyond by *Hubble* (middle; from Dumas et al. 1999) and by the Keck telescope (bottom; from de Pater et al. 2005).

(A color version of this figure is available in the online journal.)

"propeller" moons embedded in Saturn's rings (Tiscareno et al. 2010).

JWST will serve as an important window on the outer Solar System for imaging targets of opportunity such as the Jupiter impact of 2009 (Hammel et al. 2010) and the Saturn storm of 2010–2011 (Sayanagi et al. 2013).

2.4. Equinox

The next Saturn equinox will take place in 2025. The event itself will not be observable by *JWST*, as it will occur when Saturn is near the Sun as seen from Earth, but low Sun angles will be observable approximately three months before and after equinox. This will facilitate the observation of seasonal phenomena such as spokes (Figure 4), which are prevalent near equinox and absent near solstice (Mitchell et al. 2006, 2013). *JWST* will have sufficient resolution to continue monitoring spokes, as has *HST* (McGhee et al. 2005), which will have particular value as the *Cassini* mission will have ended in 2017. *JWST* will also be able to improve on the tracking of clumps in and around the F Ring near equinox (McGhee et al. 2001) and will enjoy optimal edge-on viewing of Saturn's dusty E and G rings[12] during this season (de Pater et al. 1996, 2004).

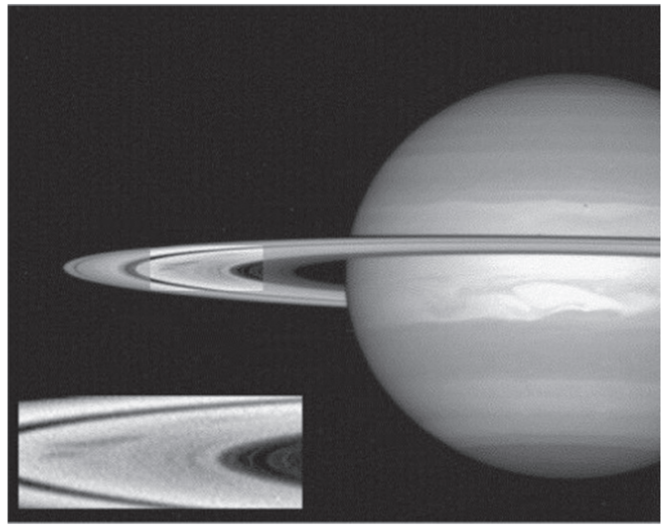

Figure 4. The ghostly radial markings known as spokes, shown in the highlighted portion of this 1996 *Hubble* image of Saturn and its rings (McGhee et al. 2005), trace the interplay of interplanetary impacts and magnetic forces in Saturn's rings. *JWST* will continue to track the seasonal behavior of spokes after the end of the *Cassini* spacecraft mission (Tiscareno 2014a).

Neither Uranus nor Neptune has an equinox that falls within the *JWST* mission (Figure 5). During the *JWST* mission, Sun angles will decrease at Neptune and will increase at Uranus. This will lead to increasingly favorable viewing for both systems as the *JWST* mission progresses since Neptune's rings are primarily dusty while Uranus's rings are dense and sharp-edged. The only exact equinoxes possibly observable by *JWST* will be at Jupiter; these will provide optimal viewing of vertical structure in the halo/gossamer rings.

2.5. Commissioning Observations and Multi-instrument Observation Opportunities

The rings and small satellites discipline does not currently have any clear candidates for observations to be carried out during *JWST* commissioning or for observations to test *JWST*'s multi-instrument capabilities.

[12] The Phoebe ring, which lies in Saturn's orbit plane and is *always* edge-on as seen from Earth, is thus always available for optimal edge-on viewing.

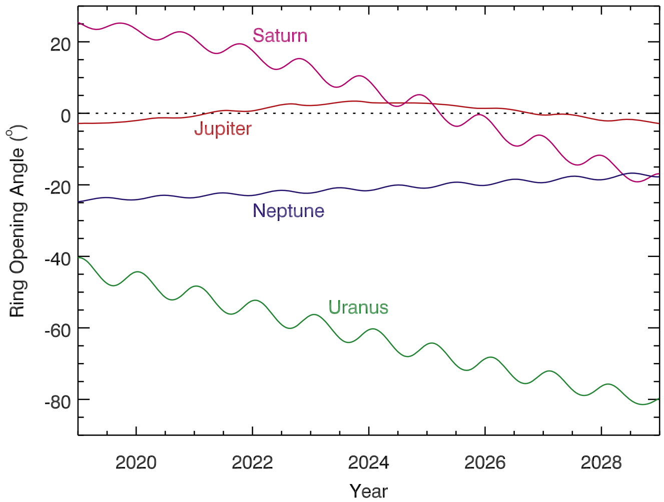

Figure 5. Opening angle as a function of time for known ring systems from 2019 to 2029 (Meeus 1997). The first half of this interval corresponds to the *JWST* prime mission.

(A color version of this figure is available in the online journal.)

3. Requirements

3.1. Stray Light and Extended Point-spread Functions (EPSFs)

Because faint rings and small moons are often in close proximity to the bright planet about which they orbit, it is important to characterize the stray light and EPSF of *JWST* instruments to determine how close to the planet an object can be and still be observable.

The point-spread functions are well characterized for point sources within the field of view, but EPSFs need to be compiled from these for extended objects, especially when the planet is off the edge of the field of view. Preliminary analysis of stray light should also be characterized through studying the blueprints of the telescope and instruments, and later by testing on the ground after the spacecraft is built. It should be kept in mind that the severity of stray light might be different at different wavelengths. The limited roll ability of the *JWST* spacecraft, which can rotate about the line-of-sight axis by only $\pm 5°$, makes this issue more pressing, as it largely eliminates the strategy of rotating the field of view so as to spatially separate the observation target from stray-light artifacts.

3.2. Color Filters

Imaging of faint objects is enhanced at wavelength bands in which the planet is dim, especially at absorption features of atmospheric constituents such as methane (see Section 2.1). The methane absorption feature at 2.3 μm is strong and corresponds to a wavelength at which water ice is bright. However, *JWST* does not have a filter centered on 2.3 μm (Gardner et al. 2006; Milam et al. 2016). Study is needed to determine whether imaging at 2.3 μm might be facilitated by selecting the appropriate wavelength of a NIRSpec cube using the integral field unit mode (Gardner et al. 2006) and also whether this mode offers imaging quality as envisioned in Section 2.1. This is especially germane for Jupiter and Saturn, which are too extended to provide a basis for adaptive optics, giving *JWST* a more pronounced advantage over ground-based telescopes. Study is also needed to determine whether filters centered on methane's 1.8 μm and on 3.4 μm bands can offer comparable imaging quality.

3.3. Coronagraphy

Both imaging and spectroscopy of faint objects (Sections 2.1 and 2.2) can be enhanced near a bright planet by using the NIRSpec instrument in its Microshutter Array (MSA) mode, which suppresses the brightness of the boresighted planet by a factor of 10^4 while taking spectrally resolved images. Stray-light problems (see Section 3.1) would likely be minimized with the bright planet on the boresight, increasing the attractiveness of this technique.

Further study is needed to characterize whether the MSA mode will facilitate good observations of faint rings or moons. For example, is the attenuation of the planet by 10^4 sufficient? Would the angular size of Jupiter render it too large to be suppressed by this technique?

3.4. Stellar Occultations

Stellar occultations, in which the brightness of a star is continuously monitored as it passes behind a semi-transparent object such as a ring, can distinguish very fine structural details, often superior to the detail discernible by direct imaging, albeit along only a single dimension (e.g., Bosh et al. 2002; Hedman et al. 2007). Occultations are an excellent method for determining the precession rates of rings, leading to tight and otherwise unobtainable constraints on planetary interiors (e.g., Nicholson et al. 2014). Occultations require that *JWST*'s trajectory be predicted precisely enough that potential occultations can be reliably identified ahead of time, that pointing be accurate enough to keep the star within the single-pixel field of view, and that readout time be fast enough to maximize the spatial resolution of the data (Santos-Sanz et al. 2016).

A minimum useful readout time (i.e., maximum useful cadence) is set by signal to noise. A high cadence will be especially important for Uranus, as its rings will be oriented roughly perpendicular to the stars' velocity as seen by *JWST*. Spectrally integrated brightness measurements are adequate, though spectral resolution would yield information about the particle-size distribution (e.g., Hedman et al. 2013).

In principle, occultations of smaller targets would also be very valuable, as occultations are currently the only method available for probing structures such as Chariklo's rings

(Braga-Ribas et al. 2014). However, the small angular size of such targets makes occultations of suitably bright stars uncommon and, combined with the uncertainty in predicting *JWST*'s trajectory, makes it difficult to predict whether occultations will occur with sufficient accuracy.

Technical details regarding the feasibility of occultations with *JWST* can be found in the companion paper by Santos-Sanz et al. (2016), who find that the current *JWST* planning ephemeris yields excellent occultation opportunities for Saturn, Uranus, and Neptune between 2019 and 2022.

3.5. Target Acquisition, Pointing Accuracy, and Exposure Duration

Exposure durations should be available for at least the period of time that it takes for a target moon to move by one pixel. To increase the integration time beyond that interval, co-adding of images will be needed in any case. The moon with the highest known apparent velocity (relative to its planet's velocity) is Metis, at 0.5 arcsec minute^{-1} when in conjunction with Jupiter, though all moons move considerably slower on the sky near their greatest elongations. Pointing accuracy should be finer than a few tenths of a pixel.

4. Conclusions

JWST promises to be an unprecedentedly valuable observatory for observing planetary rings and their attendant small moons (Tiscareno 2014a). We encourage the observing community to use the ideas in Section 2 to formulate observation plans. We encourage the *JWST* project to address the items in Section 3, to the extent possible, in order to ensure the highest possible quality of observations. Because the post-launch servicing missions that were crucial to the success of *HST* will not be possible for *JWST*, it is imperative for both communities to identify and resolve any outstanding issues now or in the near future.

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