Observing the Irregular Moons of Uranus by a Uranus Flagship Mission

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PART 1: POTENTIAL GROUND-BASED SUPPORT

1 Introduction

This poster presents the benefits of observing the Irregular moons of Uranus (and other giant planets) from a spacecraft (S/C) in orbit around the planet, such as the Uranus Flagship Mission (UFM). It covers the content of the **Uranus Flagship Workshop abstracts by Verbiscer *et al.* (#8187) and Denk *et al.* (#8169)**.

The unique viewing geometries available to UFM enable the acquisition of several **basic physical parameters** of the Uranian Irregular moons that are difficult or impossible to get from Earth:

- Close proximity (100-1000x closer than from Earth) enables acquisition of high SNR lightcurves for objects ≲ 3 km.
- Access to nearly the full range of solar phase angles, whereas the size of Earth's orbit restricts observations from it to phase angles <3°.
- From UFM, Irregulars may "hover" above or below the ecliptic plane, a highly diagnostic viewing geometry for pole/shape determination never seen from Earth.
- Viewing geometries from UFM change significantly within ***months***, compared to ***decades*** from Earth.
- ***The first large orbits with the S/C being too far from the planet to conduct other Uranus science present ideal opportunities for Irregular moon campaigns.***
- ***A targeted flyby of an Irregular moon with high-resolution images and spectra is a viable and highly encouraged objective for a Uranus flagship mission.***

2 The Uranian Irregular Moon System

- Size of Uranus' Hill sphere: 70.1×10^6 km = 0.469 au = 2740 R_{Uranus}
- Nine Uranian Irregular Moons are currently officially known (Table 1)
- Discovered between 1997 and 2003 [1-3]
- R magnitude range: ~21 – ~25.5 [2,3]
- Size range: ~18 – ~160 km [3, 4] (Table 1)
- More discoveries to be announced soon (down to ~27 mag) [5]
- Distances to Uranus (orbit semi-major axes): ~4×10^6 – 21×10^6 km [2,6]
- Highly eccentric and inclined orbits (Table 1) [6]
- All known orbits are highly tilted (>10°) relative to Uranus' orbital plane [6] (Fig. 1)
- Likely >100 objects with sizes >1 km → similar to the Jupiter and Saturn populations? (Current census: Jupiter 87; Saturn 122.)
- Largest object Sycorax (~160 km [4]) similar in size to largest Jovian Irregular (Himalia; ~140 km [7]), but smaller than Saturn's Phoebe (213 km [8]) and Neptune's Nereid (340 km [9])

3 Ground-Based Observations

- Objects are dark (p_V ~ 0.06) and close to a large, bright planet → large apertures needed for suitable SNR
- Determine orbital elements [6] (Table 1)
- Sizes estimated from apparent magnitudes [3], rarely from thermal fluxes [4,12]
- Colors at limited SNR [13-17]
- Lightcurves from K2 (Fig. 2) → Rotation periods; a/b axes ratios (Table 1)
- ELT and LSST (Vera Rubin Obs.) may improve data base for largest moons (R < 24)

4 Upcoming Stellar Occultation Opportunities

- Uranus crosses the galactic plane in 2032-2033, dramatically increasing the background star density and thereby the number of stellar occultation opportunities. (See [18] and related poster #8149 by Porter *et al.*)
- We identified 47 viable stellar occultation opportunities by Uranian Irregular moons 2024-2035. (Fig. 3 shows three of these.)
- Need to observe these events *before* 2035, after which their numbers decrease.

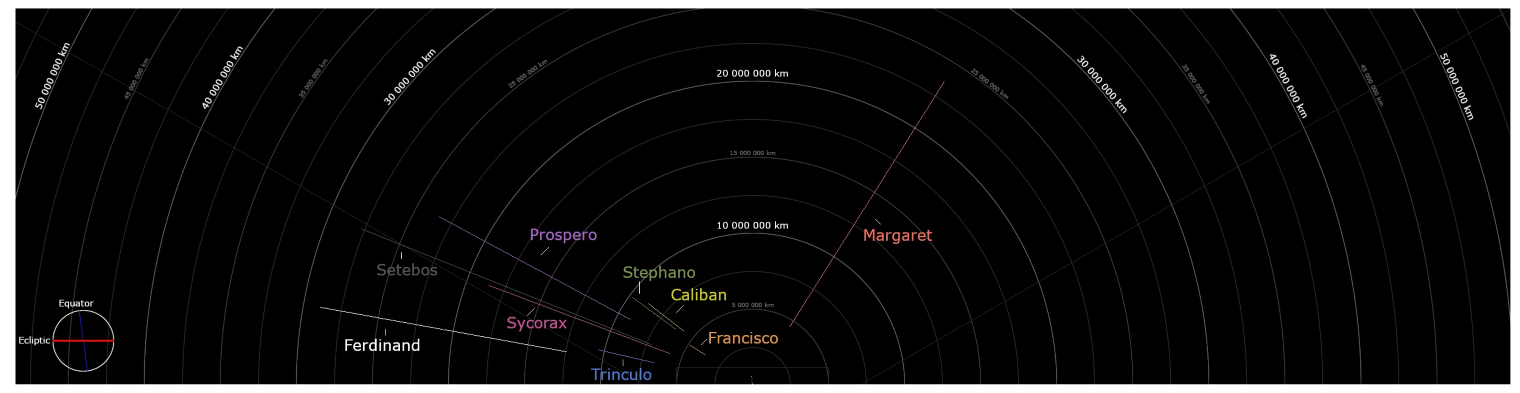

Fig. 1: Orbital distances and inclinations of the nine known Irregular moons of Uranus as well as their periapses and apoapses (scale in original file: 1 px = 40,000 km). [10]

Table 1: Uranus' Irregular moons: Orbital elements and periods, apparent and absolute magnitudes, sizes, object rotations

Satellite	JPL code	a (Gm)	e ( )	i (°)	P (d)	R (mag)	H (mag)	Diameter (km)	Rot. curve amplitude (mag)	a/b	Rotation Period
Margaret	723	14.07	0.68	58	1648	25.2	12.7				
Francisco	722	4.28	0.14	147	267	25.0	12.9	22			
Caliban	716	7.23	0.20	142	580	22.4	9.0	42	0.16	1.15	9.9484 h ± 1 m
Stephano	720	8.00	0.22	144	677	24.1	11.6	32	>0.4 ?		
Trinculo	721	8.51	0.22	167	750	25.4	12.7	18	>0.4 ?		
Sycorax	717	12.18	0.52	159	1289	20.8	7.5	157	0.121	1.1	6.9162 h ± 5 s
Prospero	718	16.27	0.44	152	1980	23.2	10.5	50	0.41	1.4	14.290 h ± 11 m
Setebos	719	17.44	0.59	158	2229	23.3	10.7	47	0.27	1.25	8.510 h ± 2 m
Ferdinand	724	20.65	0.40	170	2816	25.1	12.5	21	0.54	1.6	23.7 h ± 0.5 h

Notes: Orbital elements and orbit sidereal periods (a,e,i,P) from JPL SSD URA116 [6]. The longest period is 7.7 years or ~1/11th Uranus orbit around the Sun. R magnitudes from [3]; H (absolute V magnitude) values from [11]. Diameters of Caliban and Sycorax from [4], others from [3]. Rotation-curve amplitude of Stephano and Trinculo from [16], all others from [4]. Minimum ratio of the equatorial prime axis of each object (a/b) is calculated from lightcurve amplitudes. Rotation period values calculated from [4] assuming double-peaked lightcurves.

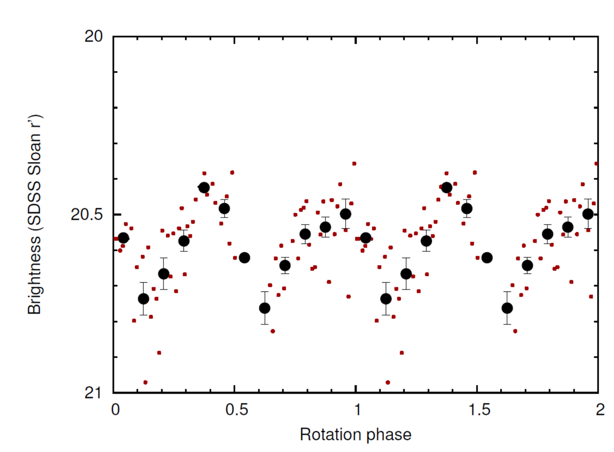

Fig. 2: Double-peaked rotation curve of Sycorax, the largest Uranian Irregular moon, from the Konkoly Observatory 1m-RCC telescope (large dots) and K2 (small red dots), reveals a rotation period of P = 6.9162 h (adapted from [4]).

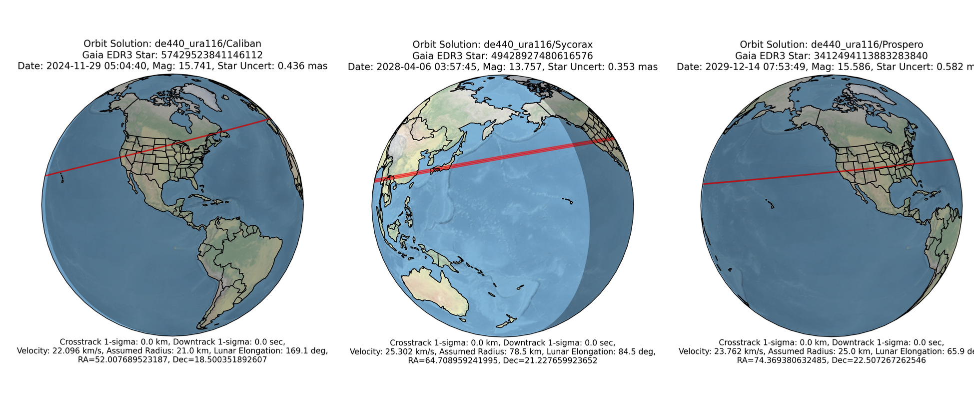

Fig. 3: Upcoming stellar occultation opportunities across the US for Caliban (2024, left), Sycorax (2028, middle), and Prospero (2029, right). Red lines show the paths of the moon's shadow cast onto the Earth, equivalent to the moon's diameter. See [18] and Porter+ poster for more details about observing stellar occultations.

Fig. 4: Solar phase angles and high ecliptic latitude views of Irregular moons potentially available to a S/C, compared to observations from Earth or Earth orbit. *Top:* S/C observes Irregular moon at low phase; *bottom:* at high phase. From Earth, only low phase is possible.

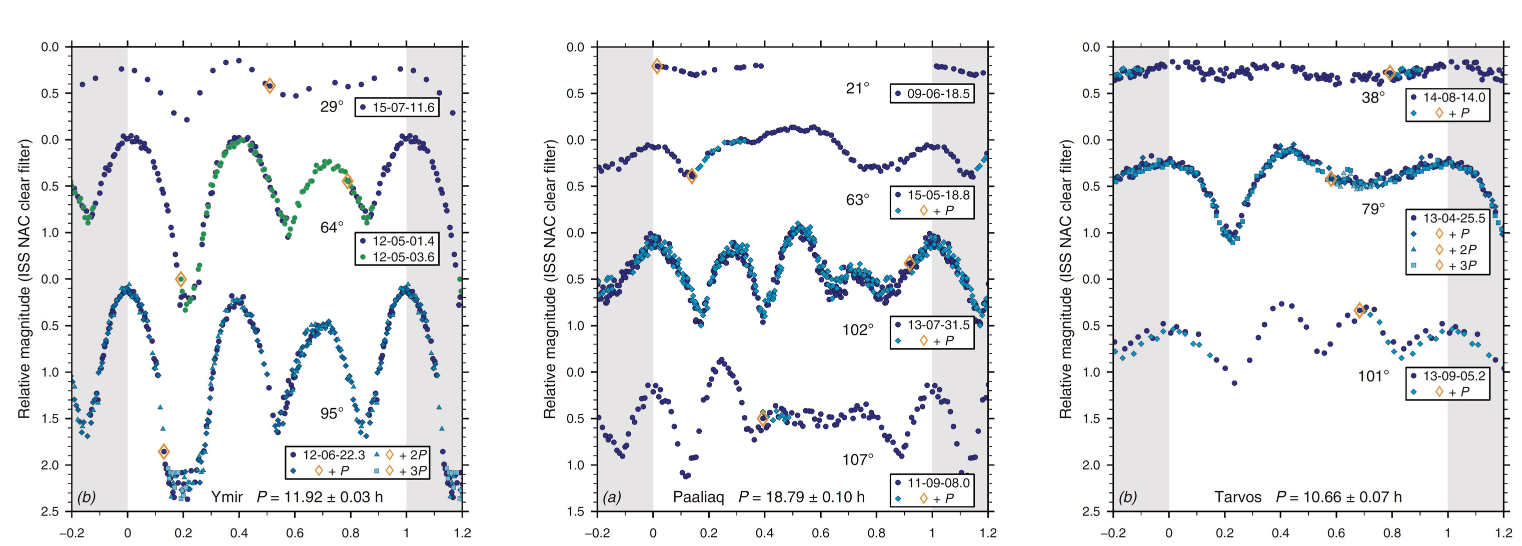

Fig. 5: Lightcurves of Saturnian Irregular moons Ymir (left), Paaliaq (middle) and Tarvos (right) from Cassini, obtained at multiple phase angles, show very different patterns [19]. Lightcurve amplitudes and number of peaks increase with increasing phase angle, enabling determination of the moon's rotation pole and shape. Note the differences between the lightcurve shapes at similar phase angles for each moon, indicating that these moons have very different shapes [8,19,22].

PART 2: SPACECRAFT OBSERVATION CAMPAIGNS

5 Observing Irregular Moons by Spacecraft

- Distances "observer to object" at order of 10 million, not billions, of kilometers [8,19]:
  - Factor ~100-1000x closer (Fig. 4)
  - Much smaller optics works to get good data, but still sub-pixel
  - Increased astrometric precision [20]
  - *History note:* Voyager-2 (1986) approaches (unknown at this time): Closest: 2.4×10^6 km (Francisco); farthest: 15×10^6 km (Margaret)
- Repeated imaging over many hours or even days:
  - Get rotation curves (lightcurves)
- Potential science to obtain with a *single* observation session per object:
  - Synodic rotation periods (at minutes accuracy); a/b axes ratios for many objects
- Potential science to obtain with *multiple* observation sessions per object:
  - Sidereal rotation periods (potentially at milliseconds accuracy)
  - Unambiguous pole-axis orientation (at a few degrees accuracy)
  - Low-order convex-shape models
  - Solar phase curves
  - Object semi-axes ratios (a/b, c/a)
  - Object absolute sizes (if one diameter can be determined by another method)
- Advantages for spacecraft:
  - Access to full range of solar phase angles (Fig. 4)
    - Observations from Earth limited to phase angles <3°
    - Spacecraft: Geometrically no limit (depending on orbit), just object brightness and Sun-avoidance constraints by S/C
    - Lightcurves acquired at larger phase angles often have significantly higher amplitudes with additional peaks (Fig. 5 (left); Fig. 13 in [19])
  - 180°-longitude ambiguity for the pole/ shape solution [21] → Fig. 4
    - Ground-based: Yes (observer, object, Sun in same plane (~ ecliptic))
    - Spacecraft: No (object often >10° above/below ecliptic as seen from S/C)
  - Observer day/night cycle limitations:
    - Ground-based: Yes (24 h)
    - Spacecraft: No (observation session over several days in principle possible; restricted by S/C engineering requirements)
  - Weather/atmospheric issues and scattered light from nearby planet:
    - Ground-based: Yes
    - Spacecraft: No ("perfect" photometric conditions)

6 Cassini's Campaign at Saturn

Cassini conducted the first campaign to observe Irregular moons with a spacecraft orbiting the host planet [8,19] (Fig. 5), resulting for Saturnian Irregular moons in:

- 24 new rotation periods [19]
- >12 pole and shape solutions [22]
- >13 phase curves at solar phase angles up to 143° [23]

7 JUICE at Jupiter

- Observation campaign [24] with the JANUS camera [25] of JUICE is envisioned
- Single observations of >50 objects to find rotation periods in principle possible; but restricted by competing science requirements
- Pole/shape solutions and phase curves for >30 Irregulars in principle possible; same restriction
- Especially approach phase and first two orbits are useful (lower competition)
- Small moons (D ~ 1 to 5 km); each is a potentially good target twice in the mission for a few weeks or months while at low phase and apparent magnitude ≲ 17 mag.
- Synodic orbit periods of Jovian Irregulars between ~0.4 and ~2.1 years; JUICE orbit tour ~3.4 years → each Irregular passes opposition ~2x during the JUICE orbit tour
- No close (targeted) flyby currently planned
- No observations of Irregular moons currently planned with Europa Clipper

8 Uranus Flagship Mission at Uranus

We strongly recommend the implementation of a campaign to observe the Irregular moons of Uranus with a Uranus Flagship Mission.

- Mission duration of ~2000 d at Uranus between Fall 2044 and Dec 2049 [26]
- All nine currently known Irregular moons of Uranus will be visible to UFM at least once at low phase angle <30° (even Setebos and Ferdinand whose orbit periods are >2000 d)
- UFM should attempt a targeted flyby of a Uranian Irregular moon
  - should be included as a S/C trajectory requirement very early in the planning process
- UFM should implement a campaign to observe (or flyby) Uranian Irregular moons during the initial orbits, when S/C is too far from the planet to conduct other science
- The date of mission end in the proposed UFM scenario almost exactly falls on the first "Uranus birthday" of one of the co-authors (TD)
  → please try to keep this schedule 😉

References

Abstracts to this poster:
Part 1: Verbiscer+ 2023, abstract #8187 https://www.hou.usra.edu/meetings/uranusflagship2023/pdf/8187.pdf
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