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Cassini Observations of Saturn's Irregular Moons

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1. Introduction

With the ISS-NAC camera of the Cassini spacecraft, we obtained photometric lightcurves of 25 irregular moons of Saturn. The goal was to derive basic physical properties of these objects (like rotational periods, shapes, pole-axis orientations, possible global color variations, ...) and to get hints on their formation and evolution. Our campaign marks the first utilization of an interplanetary probe for a systematic photometric survey of irregular moons.

The irregular moons are a class of objects that is very distinct from the inner moons of Saturn. Not only are they more numerous (38 versus 24), but also occupy a much larger volume within the Hill sphere of Saturn. Further, they are quite small: All but Phoebe have sizes in the range ~40 km to ~4 km. Therefore, they significantly contribute to the number, but not to the overall mass of Saturn's moon system (< 0.01%). Widely accepted is the hypothesis that many irregular moons have joint progenitors and form "collisional families". A comprehensive summary on Saturn's irregulars is given by Denk *et al.* (2018) [1]. Earlier summaries on all irregular-moon systems of the giant planets can for example be found in [2], [3], or [4].

2. Lightcurves and rotation periods

All 9 known prograde and 16 of the 29 known retrograde Saturnian irregulars were observed over a wide phase-angle range of ~2° to >125°. The average observation distance for Cassini was in the order of $1.4 \cdot 10^7$ km, corresponding to a spatial resolution below 80 km pxl^{-1}, too low to resolve the irregulars (except Phoebe). The brightness range during the observations was between ~9.5 and ~16.6 mag (Phoebe was occasionally brighter than ~6 mag). All lightcurves but Phoebe's are mainly or exclusively shape-driven and show 2-maxima/2-minima or 3-max/3-min patterns. An exception is a lightcurve of Paaliaq which shows pronounced 4-max/4-min.

The period range of all observed moons is between ~5.5 h and ~76 h (→ Table). The periods of all but two prograde irregulars are slower than ~13 h, while the periods of all but two retrogrades are faster than ~13 h. The fastest period (Hati) is much slower than the disruption rotation barrier for asteroids (~2.3 h), indicating that Saturn's irregulars may be rubble piles of rather low densities, possibly as low as of comets.

Table: Rotational periods of 25 Saturnian irregulars

Moon name	Approx. size [km]	Rotational period [h]
Hati	5	5.45 ± 0.04
Mundilfari	7	6.74 ± 0.08
Loge	5	6.9 ± 0.1 ?
Skoll	5	7.26 ± 0.09 (?)
Suttungr	7	7.67 ± 0.02
Kari	6	7.70 ± 0.14
Bergelmir	5	8.13 ± 0.09
Phoebe	*213* [5]	*9.2735 ± 0.0006* [6]
Fornjot	6	~9.5 ??
Siarnaq	**42**	**10.18785 ± 0.00005**
Narvi	7	10.21 ± 0.02
Tarvos	**15**	**10.691 ± 0.001**
Skathi	8	11.10 ± 0.02
Ymir	19	11.92220 ± 0.00002
Greip	5	12.75 ± 0.35 (?)
Hyrrokkin	8	12.76 ± 0.03
Ijiraq	**13**	**13.03 ± 0.14**
Albiorix	**33**	**13.33 ± 0.03**
Bestla	7	14.6238 ± 0.0001
Bebhionn	**6**	**16.33 ± 0.03**
Paaliaq	**25**	**18.79 ± 0.09**
Kiviuq	**17**	**21.97 ± 0.16**
Erriapus	**10**	**28.15 ± 0.25**
Thrymr	8	38.79 ± 0.25 (?)
Tarqeq	**6**	**76.13 ± 0.01**

Notes: Data are compiled from Tables 2 and 3 in [1], see also [7]. **Bold**: These moons orbit Saturn **progradely**. Other lines: Moons on retrograde orbits. The sizes (except Phoebe) are calculated from absolute magnitude H [8] with an assumed albedo $A = 0.06$; they may be uncertain by −30% to +50% due to uncertain values of A (approx. ±0.03) and (to a lesser degree) of H (a few tenths of magnitude). Question marks indicate that the period is uncertain; in brackets that it is likely but not completely secure.

Some objects (Siarnaq, Ymir, Kiviuq) show lightcurve amplitudes >2 mag at phase >60°. The Tarqeq period is within 0.5% of the 1:5 resonance of Titan's orbit, raising the question of tidal influence.

3. Shape, binarity, pole, color

The number of lightcurve extrema gives hints on basic shapes of the moons. Potential first-order "end-member" shapes of Saturn's irregular moons are an "ellipsoid" (2-max/2-min lightcurves even at higher phase angles; e.g., seen at Kiviuq, Erriapus, Hati, or Bestla) and a "triangular prism" (3-max/3-min lightcurves also at lower phase as seen at Ymir, Siarnaq, Hyrrokkin, and some others). Convex-shape models of Ymir and Siarnaq confirm this type of shape.

A possible interpretation of "triangular" convex shapes is that these objects might be contact-binary moons structured somehow similar to comet 67P/Churyumov-Gerasimenko. Furthermore, symmetric 2-max/2-min lightcurves with large amplitudes at low phase, slow rotational periods, plus other lightcurve structures qualify objects Kiviuq, Bestla, Erriapus, and possibly Bebhionn as binary-moon candidates.

The pole-axis of Ymir points close to the south-ecliptic pole, indicating a retrograde spin. For Siarnaq, an ecliptic lat/lon of $\lambda,\beta = 98°/-23° \pm 15°$ indicates that this moon experiences extreme seasons, somewhat reminiscent of the regular satellites of Uranus. For both moons, no hemispherical color variations could be detected on the surfaces.

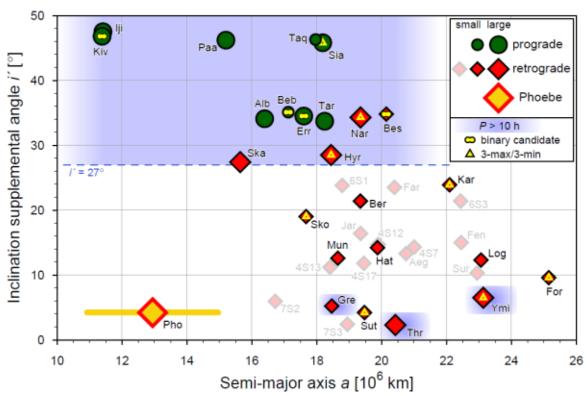

Figure: a-i' plot for Saturn's irregular moons.

Notes: Adapted from [1]. The inclination supplemental angle i' ("orbit tilt") is defined as $i' = 90° - |90° - i|$. For Phoebe, periapsis and apoapsis are also shown (yellow bar). The bin "large" includes the 13 largest irregulars (separated at H = 14.4 mag). Pale diamonds indicate moons not observed by Cassini (their rotational periods are unknown).

4. Patterns and correlations

Among Saturn's irregular moons, the orbital semi-major axes a, the orbital senses of motion (pro-/retrograde), the orbit tilts (i'), the object sizes, and the rotational periods appear to be correlated to some degree. The prograde objects are on average closer to Saturn, on higher tilted orbits, larger in size, and slower rotators than the retrograde moons (→ Figure).

While the orbit stability is higher for retrograde objects than for progrades very far away from Saturn [9], a compelling physical cause for size and spin relations to orbital elements is not yet known. We may speculate that the progenitor objects had different material densities, with Phoebe being a potential source of one or several retrograde moon families.

5. Summary

The first ever photometric survey of irregular moons with an interplanetary spacecraft was performed with Cassini-Huygens. Disk-integrated observations of 25 irregular satellites of Saturn revealed that the individual objects are very different from each other. The data yielded rotational periods between ~¼ d and ~3 d, and lightcurve amplitudes from 0.1 to 2.5 mag. They support the hypothesis that the irregulars are of low density and potentially cometary in nature. Binary or contact-binary moons are not proven, but may well be possible. Orbit (a, i') and physical parameters (sizes, periods) appear to be correlated non-randomly, the cause is unknown.

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