CASSINI OBSERVATIONS OF SATURN'S IRREGULAR MOONS. T. Denk[1] and S. Mottola[2], [1]Freie Universität Berlin, Malteserstr. 74-100, 12249 Berlin, Germany (Tilmann.Denk@fu-berlin.de), [2]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Rutherfordstr. 2, 12489 Berlin, Germany (Stefano.Mottola@dlr.de).

Introduction: Saturn's outer or irregular moons represent a distinct class of objects in the Solar System. They were discovered between 2000 and 2007 except for Phoebe which has been photographed since 1898. The distances between Saturn and the 38 known objects vary between 7.6 Gm (126 R_S; Kiviuq periapsis) and 33.2 Gm (550 R_S; Surtur apoapsis). The irregulars are found on orbits of large eccentricity and high inclination, both prograde and retrograde.

Large moon Phoebe has a retrograde orbit and accounts for more than 98% of the total mass of Saturn's irregulars. Of the remaining mass, ~92% belongs to the nine prograde objects. All irregulars are thought to be captured objects or remnants of violent collisions between progenitor moons which have originally been captured. A comprehensive summary of the irregular moons of Saturn is for example given in [1].

Cassini observations: A highlight of Cassini was the targeted flyby of Phoebe in June 2004, just before Saturn arrival [1]. After orbit insertion, and especially during the second half of the mission since 2010, the ISS camera [2] continued to monitor the outer moons. Because these objects were far away from the spacecraft (> 10 Gm for most of the time), they appeared unresolved. The goal was to obtain photometric lightcurves to determine basic physical properties like rotation periods, colors, pole directions, and shapes. *Table 1* shows the best visual magnitudes V for each object. Useful photometric data could be obtained for objects with $V \lesssim 16.5$.

Since Cassini was located inside the orbits of the irregular moons, but the illumination source (the Sun) was far away (outside the orbits), the phase angles could take all values between 0° and 180° (see *Table 1* for ranges of actual observation phases). This unique advantage of Cassini would be given to any spacecraft orbiting a giant planet while observing outer moons.

The total number of ISS images targeting irregular moons is ~38,000, obtained during ~200 observations. Our Cassini campaign represents the first utilization of an interplanetary spacecraft for a systematic photometric survey of irregular moons in the Solar System. A detailed description is given in [3].

Rotation periods: Twenty-five irregular moons of Saturn were successfully observed with Cassini ISS. Rotation periods were determined for all of them, they range from ~5.5 h to ~76 h ([3]; see also *Table 1*). The fastest period is substantially slower than the disruption barrier of asteroids (~2 h). Indeed, about one-third of all main-belt asteroids of sizes between ~4 and ~45 km has a faster spin. This may be suggestive of a bulk density significantly lower than that of asteroids, possibly < 1 g cm^{-3}. Thus, the hypothesis that the irregulars are rubble piles and might be composed of icy material is compatible with our period measurements.

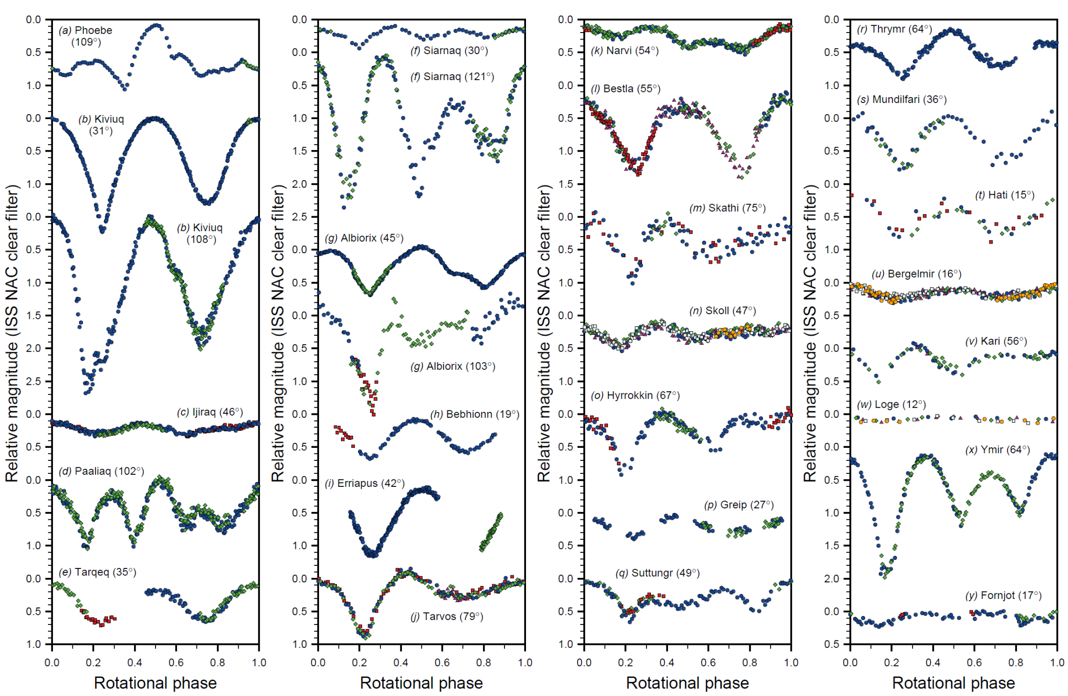

Fig. 1: Lightcurves of 25 irregular moons of Saturn, taken at the annotated phase (from [1]).

Lightcurve shapes: The shapes of the lightcurves (one or two examples for each moon are given in *Fig. 1*, more are shown in [3]) and their amplitudes vary considerably between the different objects, indicating that Saturn's irregular moons are very individual worlds with various irregular shapes. Most lightcurves show "2-maxima/2-minima" or "3-max/3-min" patterns (*Fig. 1*; column "LC" in *Table 1*). "2-max/2-min" is more common for low phase angles (≲ 45°), "3-max/3-min" for observations at higher phase.

Outstanding are lightcurves of Kiviuq, Siarnaq, and Ymir which exceed an amplitude of 2 mag at phase ≳ 80°. Convex-shape models of Ymir and Siarnaq are characterized by a triangular equatorial cross-section, possibly a convex-hull representation of contact binaries. Kiviuq must be a very prolate object; it is also a promising candidate for a contact-binary (similar to New Horizons's target (486958) 2014 MU_{69}) or even for a binary moon.

References: [1] Denk, T., *et al.* (2018): The Irregular Satellites of Saturn. *In:* Enceladus and the Icy Moons of Saturn (Schenk, P.M., *et al.*, eds.), Univ. Arizona Press, 409-434. [2] Porco, C.C., *et al.* (2004): *Space Sci. Rev.* **115**, 363-497. [3] Denk, T., Mottola, S. (2019): Studies of Irregular Satellites: I. Lightcurves and Rotation Periods of 25 Saturnian Moons from Cassini Observations. *Icarus*, in press. [4] Bauer, J.M., *et al.* (2004): *Astrophys. J.* **610**, L57-L60.

Table 1: Physical properties and Cassini observations of 25 Saturnian irregular moons.[1]

Moon name	Group member	Object size[2]	Rotation period [h][3]	$(a/b)_{min}$[4]	LC[5]	Cassini imaging observations: No. of obs.[6]	first – last (mm/yy)[6]	best mag. *V*[7]	phase [°][8]
Phoebe	retrograde	213	9.2735 ± 0.0006	1.01	1	8	08/04 – 01/15	5.1	3 – 162
Siarnaq	Inuit	42	10.18785 ± 0.00005	1.17	3	8	03/09 – 02/15	10.8	4 – 143
Paaliaq	Inuit	25	18.79 ± 0.09	1.05	4	12	11/07 – 01/17	11.2	21 – 112
Kiviuq	Inuit	17	21.97 ± 0.16	2.32	2	24	06/09 – 08/17	12.0	4 – 136
Ijiraq	Inuit	13	13.03 ± 0.14	1.08	2	11	01/11 – 04/16	11.8	40 – 104
Tarqeq	Inuit	6	76.13 ± 0.01	1.32	2	10	08/11 – 01/17	15.0	15 – 49
Albiorix	Gallic	33	13.33 ± 0.03	1.34	2,3	13	07/10 – 01/17	9.5	5 – 121
Tarvos	Gallic	15	10.691 ± 0.001	1.08	2,3	9	07/11 – 10/16	12.8	1 – 109
Erriapus	Gallic	10	28.15 ± 0.25	1.51	2	15	02/10 – 12/16	13.6	26 – 116
Bebhionn	Gallic	6	16.33 ± 0.03	1.41	2	9	03/10 – 07/17	14.6	19 – 79
Narvi	retrograde	7	10.21 ± 0.02		3	4	03/13 – 01/16	15.6	54 – 80
Bestla	retrograde	7	14.6238 ± 0.0001	1.47	2	14	10/09 – 11/15	13.5	30 – 96
Skathi	retrograde	8	11.10 ± 0.02	1.27	2	8	03/11 – 08/16	15.1	15 – 77
Skoll	retrograde	5	7.26 ± 0.09 (?)	1.14	3	2	11/13 – 02/16	15.5	42 – 47
Hyrrokkin	retrograde	8	12.76 ± 0.03	1.27	3	7	03/13 – 03/17	14.4	20 – 82
Greip	retrograde	5	12.75 ± 0.35 (?)	1.18	2 (?)	1	09/15	15.4	27
Suttungr	retrograde	7	7.67 ± 0.02	1.18	2,3	5	05/11 – 11/16	15.4	12 – 72
Thrymr	retrograde	8	38.79 ± 0.25 (?)	1.21	2 (?)	9	11/11 – 09/17	14.9	13 – 105
Mundilfari	retrograde	7	6.74 ± 0.08	1.43	2	1	03/12	15.3	36
Hati	retrograde	5	5.45 ± 0.04	1.42	2	6	02/13 – 12/15	15.3	14 – 73
Bergelmir	retrograde	5	8.13 ± 0.09	1.13	2	2	10/10 – 09/15	15.9	16 – 26
Kari	retrograde	6	7.70 ± 0.14		3	1	10/10	14.8	56
Loge	retrograde	5	6.9 ± 0.1 ?	1.04	2 ?	2	10/11 – 02/15	16.2	12
Ymir	retrograde	19	11.92220 ± 0.00002	1.37	3	9	04/08 – 07/15	13.2	2 – 102
Fornjot	retrograde	6	7 or 9.5 ± 0.4 ?	1.11	2 or 3 ?	2	03/14 – 04/14	16.4	17 – 30

[1] Table is adapted from [1]. For a high-level description of the Cassini observations, see https://tilmanndenk.de/outersaturnianmoons/.
[2] Calculated from absolute magnitude and assumed albedo of 0.06 [1]. Note that the errors may be large (up to approx. −30%/+50%).
[3] From [1]. A question mark indicates that the period is unambiguous or tentative. The Phoebe value is from [4].
[4] Minimum ratio of the equatorial axes of a reference ellipsoid with dimensions *a* and *b* (derived from the lightcurve amplitudes) [1].
[5] Amount of maxima and minima in different lightcurves of each moon (see also discussion in [1] and lightcurve plots in [3]).
[6] Number of Cassini imaging observation "requests" ("visits") where data of the object were achieved. The targeted flyby of Phoebe (10-12 June 2004) and data from optical navigation are not included in the counts.
[7] Best visual magnitude *V* of the object as seen from Cassini at a time where data were acquired (again excluding the Phoebe flyby).
[8] Lowest and highest observation phase angles during Cassini observations. Phase angles from Earth are always < 7°.