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# Discovery of the Closest Saturnian Irregular Moon, S/2019 S 1, and Implications for the Direct/Retrograde Satellite Ratio

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## Abstract

We present a tracked orbit for a recently discovered 25th magnitude irregular moon of Saturn, using Canada-France-Hawaii Telescope imaging. Our 2 yr of observational arc on the moon leads to an orbit with a semimajor axis of 11.2 million kilometers and an inclination of 44 deg. This makes it one of the smallest Saturnian irregular moon orbits known and puts the moon in the Inuit group. This moon is also a magnitude brighter than the faintest known Saturnian irregulars. We show that the moon's small semimajor axis results in it spending most of the time lost in the glare of the often-nearby planet, thus explaining how it escaped detection in previous surveys. We postulate that the disparity in the known inventory with more retrograde than direct irregular moons is partly due to the selection bias against finding the direct moons (whose groupings have smaller semimajor axis).

*Unified Astronomy Thesaurus concepts:* Irregular satellites (2027); Saturnian satellites (1427); Natural satellites (Solar system) (1089); Saturn (1426)

## 1. Introduction

The inventories of irregular moons were very sparse until the invention of wide-field CCD cameras, which allowed searching the several square-degree area, to a greater depth than photographic plates, around the giant planets in which these satellites orbit. In the decade from 2000 to 2010 dozens of irregulars around Jupiter and Saturn were detected, with fewer around Uranus and Neptune due to the inability to detect the smallest moons for these distant systems where little reflected light is available. Irregular moons have both direct and retrograde orbits (the latter being an orbital sense opposite to that which the planet orbits the Sun) and have moderate to large orbital eccentricities around their host planet; see Jewitt & Sheppard (2005), Nicholson et al. (2008), and Denk et al. (2018) for review articles on irregular moons.

Excluding the first Saturnian irregular discovered, Phoebe, only two surveys have been conducted to discover and track irregular moons around Saturn. The first was Gladman et al. (2001), which found 12 irregular moons and discovered the three inclination groupings: the Inuit group with orbital $i \simeq 46°$, the Gallic group with orbital $i \simeq 34°$, and the more dispersed Norse grouping (with possible subgroups). Members of the two former groups have direct orbits and Norse members have retrograde orbits. The second survey, by Sheppard et al. (2005), used the Subaru Telescope to hunt for Saturnian irregulars over four oppositions from 2004 to 2007; this campaign found the majority of the currently known Saturnian irregulars (45). Details on this search have never been published but a majority of the moons are discussed in both Nicholson et al. (2008) and Denk et al. (2018). A recent third survey (Ashton et al. 2021a) discovered 77 Saturnian irregular moon candidates from images taken between 2019 July 1 and July 4 (UT). The purpose of the survey was to study the size distribution of Saturnian irregulars; therefore the objects were not observed for long enough to produce orbits.

One puzzle that has emerged is that, especially for the well-populated Jovian and Saturnian system, when approaching the observational magnitude limit the surveys have detected more retrograde irregulars than direct orbits. Not including the new moon discussed here (S/2019 S 1), there are currently 10 direct to 61 retrograde Jovian irregulars, 12–46 Saturnians, 1–8 Uranians and 3–4[5] Neptunians. While it is understood that (because of the physics of the restricted three-body problem) retrograde moons can remain stable at somewhat larger semimajor axes than direct orbits, the preponderance of retrograde orbits is often interpreted as primordial due to their greater stability (Nesvorný et al. 2003; Denk et al. 2018). However, the brightness of the host planet could result in a bias in the detection of irregular moons. Sheppard et al. (2005) found that scattered light from Uranus was significant when within 3.5′ from the planet. This is only 4% of the Hill radius of the Uranus, although for the significantly brighter gas giants, Jupiter and Saturn, a larger fraction of the Hill sphere will be affected by the planet's scattered light. As part of a search to push the Jovian limit down to kilometer-scale moons, Ashton et al. (2020) pointed out that because direct moons tend to have smaller semimajor axes, their detection will be systematically hampered by their being much more frequently close to the near-blinding glare of their bright host planet. This could thus explain at least some of the imbalance between the detected number of retrograde versus direct irregular moons.

This paper announces the discovery and tracking of a new Saturnian irregular, S/2019 S 1. We present the orbit of this newly discovered moon and discuss its detectability and the detectability of moons with similar orbits. Lastly we show that

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[5] These numbers include retrograde Triton and direct Nereid. Triton's classification as "irregular" is debatable; here we base it on Triton not having a direct orbit sharing the planetary rotation plane.

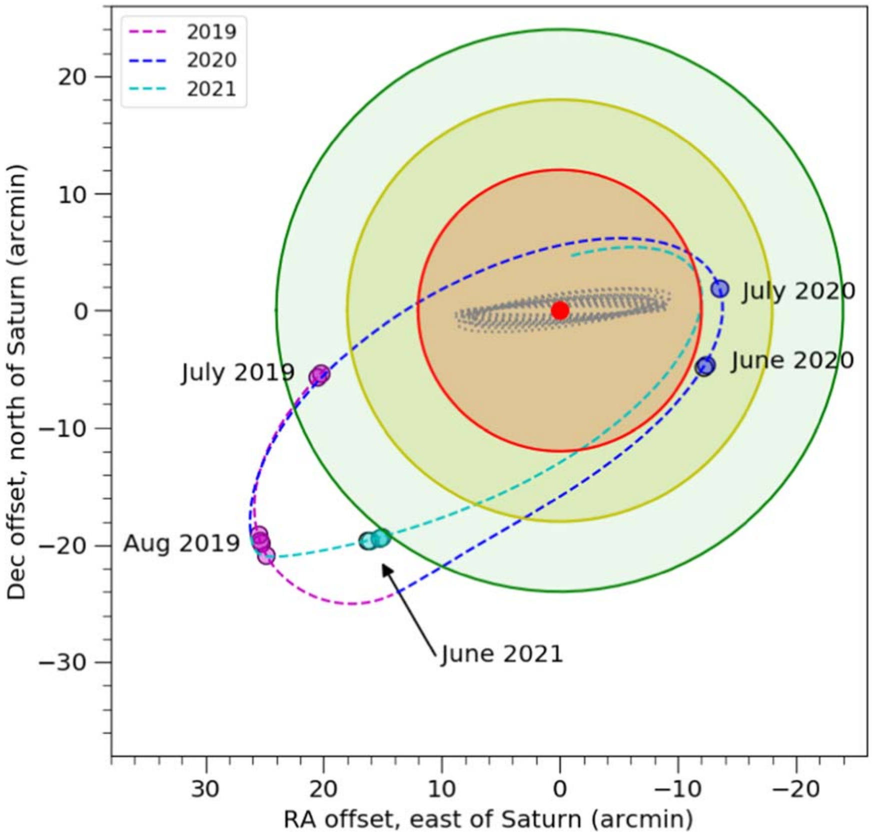


**Figure 1.** Offset of S/2019 S 1 relative to Saturn (red dot). Colored circles represent a detection of the moon, with the dashed line showing the best-fit orbit (as seen from moving Earth; hence the Saturnocentric orbit does not close). Each color represents a different calendar year, with the 2019 (purple) arc starting from 2019 July 1. Also shown is the projected orbit of the outermost regular moon, Iapetus, during the same time frame (gray dotted line). Three shaded circles centered on Saturn, with radii of 12′ (red), 18′ (yellow), and 24′ (green), indicate plausible regions of severe, moderate, and mild scattered light (see text).

the small direct orbit of S/2019 S 1 is in agreement with the idea that direct irregulars are harder to detect compared to their retrograde counterparts.

## 2. Current Data Set and Reduction Methods

### 2.1. Discovery

The Ashton et al. (2021a) search consisted of two 1.1 square-degree Canada-France-Hawaii Telescope (CFHT) MegaCam fields on either side of Saturn, with the nearside of the field being ∼7′ away from the planet. In total, 120 objects were detected moving near Saturn's on-sky rate, of which 43 have now been linked to previously known moons. The brightest detection that was not linked was internal designation e26r58a12, with $w$-band magnitude $m_w = 25.1$ and thus a rough diameter 5 km. This moon was detected (Figure 1) about 20′ east of the planet in 2019 July and is about a magnitude brighter than the faintest Saturnians with IAU designations.

### 2.2. Tracking

In an attempt to track some the of the newly discovered moons, the offset observations were repeated in the last week of 2019 August, two months after discovery, and in two dark runs near opposition in 2020. A potential recovery of e26r58a12 was found in the images taken two months after discovery: on 2019 August 23, 26, and 27, and September 3. A preliminary orbit from the 2 months arc allowed us to track the moon to 2020 June 27/28 and July 20, where the moon had moved to the other side of Saturn. Using a dedicated search from CFHT Director's Discretionary Time, the moon was detected on 2021 June 8, 9, 13, and 14 at the predicted position of the updated orbit back on the east side of Saturn, thus confirming without a doubt the legitimacy of this moon and its orbit. Astrometry of e26r58a12 was submitted to the IAU Minor Planet Center, which confirmed the high quality of the astrometric observations (rms residual of 0.″16) and gave the moon the temporary IAU designation S/2019 S 1 (Ashton et al. 2021b).

## 3. Orbit

Fitting the whole available arc of S/2019 S 1 produces the Saturnocentric orbital elements in Table 1. We remind the reader that irregular moon orbits precess relatively quickly, so these osculating Saturnocentric elements are valid to high precision during a limited time period. With an inclination of 44.°4, S/2019 S 1 is obviously a member of the Inuit group. The moon has a semimajor axis that is very similar to two previously known Inuit members, Kiviuq and Ijiraq, which have the smallest semimajor axes (of ≃11, 200,000 km) of the known Saturnian irregular moons. This makes S/2019 S 1 one of the smallest-orbit known Saturnian irregulars. Further, the eccentricity of S/2019 S 1, with a value of 0.623, makes it one of the the most eccentric irregular moons known and bringing it closest to Saturn of any irregular. The similarity in inclination and semimajor axis means that S/2019 S 1 plausibly comes from the same parent body whose fragmentation produced

**Table 1**
Orbital Elements for S/2019 S 1

| | |
|---|---|
| Semimajor axis, $a$ (km) | $11.2 \times 10^6$ |
| Eccentricity, $e$ | 0.623 |
| Inclination, $i$(°) | 44.4 |
| Longitude of ascending node, Ω(°) | 159.5 |
| Argument of pericentre, $\omega$(°) | 106.2 |
| Modified Julian Date of pericenter passage | 59518.23 |

**Note.** The epoch for the elements is MJD 59600.5 and the J2000 ecliptic is used as the reference plane.

Ijiraq and Kiviuq; the latter's light curve shows it to be extremely irregularly shaped (Denk et al. 2018), supporting the scenario that even those two larger moons are also collisional fragments of some originally larger captured moon. However, since the eccentricity of S/2019 S 1 is significantly larger than either Ijiraq or Kiviuq, a high-speed collision would be needed to produce the eccentric orbit of S/2019 S 1; Kiviug's extreme shape could also be linked to an especially catastrophic fragmentation.

## 4. Discussion and Conclusion

### *4.1. Detectability*

The fact that this brightest new irregular from the Ashton et al. (2021a) search is a direct moon with small semimajor axis gives additional support to the hypothesis made by Ashton et al. (2020) in the Jovian search: there is some level of discovery bias toward finding retrograde irregulars compared to those with direct orbits. The logical question is thus: Why was this moon not detected during the four oppositions that Subaru was observing Saturnian irregulars, when moons that are approximately a magnitude fainter were found? (We note that the moon is far too faint to have been detected in the original Gladman et al. (2001) search at any point in its orbit.) We suspect that scattered light near the planet is the likely culprit.

We somewhat arbitrarily define three zones that are within 12′, from 12′ to 18′, and from 18′ to 24′ of Saturn (shown in Figure 1 in red, yellow, and green, respectively). The mosaic CCDs that were closest to Saturn in the CFHT search performed by Ashton et al. (2021a) were mostly in the yellow zone. Through the use of artificially implanted moon signals, Ashton et al. (2021a) found that these CCDs had a limiting magnitude that was 0.3–0.4 mag brighter than the CCDs farthest from Saturn. Thus, for CFHT, the yellow zone probes about 0.3–0.4 mag less faint into the irregular population. The amount the detection efficiency drops when close to Saturn is similar to what Sheppard et al. (2005) found for Uranus, although at a much larger angular separation since Saturn is significantly brighter than Uranus. The green zone likely has a a smaller (≃0.1 mag) depth degradation, while the red zone likely has much more than half a mag of depth loss. This measurement is representative but not easy to generalize to other telescope imaging cameras. This moon detectability loss depends sensitively on a telescope's baffling to minimize stray light from nearby bright sources, i.e., the host planet. Compared to other wide-field imaging telescopes we have used, CFHT has relatively good baffling, which reduces the amount of general scattered light and internal reflection artifacts from bright sources just off the mosaic camera. Other telescopes may have larger limiting magnitude losses in each zones (which in general are only roughly circularly symmetric around the bright source due to specific reflections off of telescopic support structures).

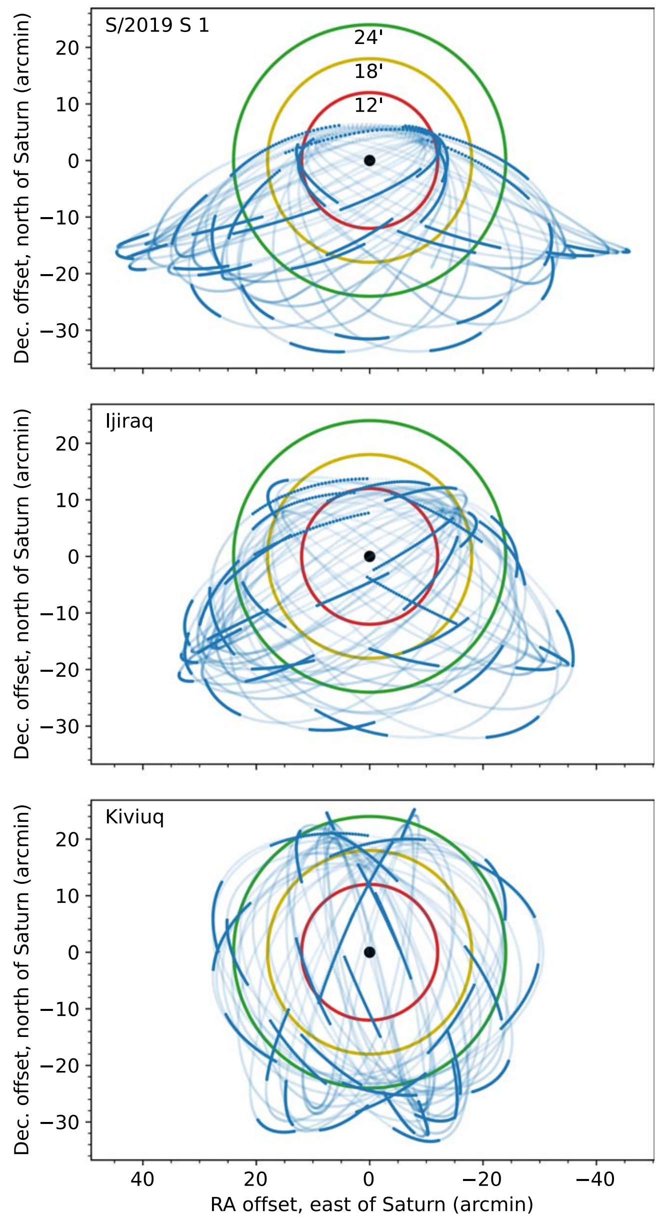


**Figure 2.** Predicted orbits of S/2019 S 1 (top panel), Ijiraq (middle panel), and Kiviuq (bottom panel) from 1990 to 2026 at 1 day intervals. When a moon is within 20° of opposition it is represented by a large blue dot, when it is not within 20° it is represented by a smaller faded dot. The boundary of the red, yellow, and green zones are indicated on each panel.

We calculated the ephemeris of S/2019 S 1 from 1990 to 2026 and determined its offset from Saturn at 1 day intervals (see top panel of Figure 2). We then calculated the fraction of time that the moon is within each of the three zones, while Saturn is within 20° of opposition (which is when detection surveys would typically be conducted). We find that S/2019 S 1 spends 12% of its time within 12′, 29% within 18′, and 39% within 24′. These percentages are cumulative. Depending on how strong the scattered light is in a particular telescope imaging system, these percentages indicate that just detecting the moon will be hampered a significant fraction of the time.

**Table 2**
Fraction of Near-opposition (<20°) Time a Moon is within a Given Angular Distance from Saturn between the years 1990 to 2026

| Moon | <12′ | <18′ | <24′ |
|---|---|---|---|
| S/2019 S 1 | 11.8% | 29.3% | 38.9% |
| Ijiraq | 10.4% | 26.3% | 48.4% |
| Kiviuq | 11.7% | 18.2% | 42.8% |

**Note.** These percentages are cumulative.

An additional important consideration is that detection in a single dark run does not confirm a moving source to be a moon. Instead, the designation of a moon requires it to be tracked over multiple dark runs before it can be confirmed that an object is in orbit around a planet. Given that moons frequently plunge into glare, multidark run detection is even more difficult. As Figure 1 shows, we were fortunate to have S/2019 S 1 moving away from the planet at our initial detection in 2019 July so that our tracking data 8 weeks later still had the moon available; at a random search epoch where such a moon is far enough away to be found, the probability that two dark runs later it will *also* still be far enough from the planet is not large. This is difficult to quantify in general, but Figure 2 shows that it will be common that by ±2 dark runs S/2019 S 1 will often be in the planet's glare if the discovery was at opposition.

### *4.2. Detection Biases Relative to other Moons*

With $e = 0.623$, S/2019 S 1 has one of the largest eccentricities for an irregular moon, and thus would typically have a larger maximum separation from Saturn than a moon with the same semimajor axis but smaller eccentricity. Thus we decided to repeat the separation experiment with Kiviuq and Ijiraq, which have more common irregular eccentricities, of about 0.3. As can be seen in Table 2, Kiviuq and Ijiraq spend roughly the same amount of time within each zone compared with S/2019 S 1.

Spending such a large fraction of time within the glare of Saturn presents less of a problem for detecting Kiviuq and Ijiraq because they are bright and were thus easily discovered by Gladman et al.'s (2001) shallow survey. However, if these two moons were instead as faint as S/2019 S 1, then they would be just as hard to detect compared with S/2019 S 1. Again, it takes observations over at least a few dark runs to confirm the validity of a moon. Thus it is likely that a moon with an orbit similar to Kiviuq and Ijiraq and with a magnitude close to the survey limit would often not be observed at all, or not acquire multiple dark runs within a single discovery season. Kiviuq, Ijiraq, and S/2019 S 1 have the smallest semimajor axes of the known Saturnian irregulars, and are therefore the most extreme cases.

Ashton et al. (2021a) stated that S/2019 S 1 is at the completion limit for Saturnian irregular moons, since it was the brightest previously unknown moon that they found. If this is true, then even in the worst-case scenario the population of Saturnian irregulars down to this limit is unaffected by Saturn's glare, and would thus have no biases. The ratio of direct-to-retrograde for the Saturnian system down to the limit is 10:17, which strongly indicates that the imbalance in orbital direction is intrinsic. If this ratio of 10:17 continues down to the smallest known Saturnian irregular then there are 14 direct moons that are larger which have yet to be detected; this is assuming that the retrograde moons are complete down to the smallest one detected.

Since the ice giants are significantly fainter than the gas giants, the effect of the host planet on the detection bias of moons of Uranus and Neptune should be smaller, or even negligible. Neptune does appear to have a similar number of direct-to-retrograde moons, with three to four (or 2:3 if Triton and Nereid are excluded). However, there are 8 times as many retrograde Uranian irregular moons as direct (1:8) and, as such, the Uranian irregular system does not support an intrinsic equality between directs and retrogrades. Both ice giants have low numbers of irregular moons, thus better statistics are needed before concrete conclusions can be made.

Looking at the "classical" irregular moons of Jupiter (i.e., those found before the use of CCDs) the ratio of direct-to-retrograde moons is 4:4. In the case of the Saturnian irregulars discovered by Gladman et al. (2001) and Phoebe the ratio is 7:6. Thus the direct-to-retrograde ratio for "big" irregular of moons of Jupiter and Saturn is almost 1:1. This could either be a piece of evidence supporting intrinsic capture equality or that collisions are causing the discrepancy in the ratio. By the latter we mean that the "big" irregulars are original captured objects (or their largest fragments) and the smaller irregulars are collisional fragments preferentially produced for some reason on the retrograde side. There is no obvious reason collisions would favor destruction in the retrograde side, but neither does capture (e.g., Nesvorný et al. 2014). If one thinks only about Saturn and Jupiter, then the chance that the biggest recent collisions occurred on the same sense for both planet is 50% (since if both had heavily populated direct spaces, the same question would be raised). We would again like to remind the reader that the numbers of Uranus and Neptune irregulars, along with the "big" irregulars of Jupiter and Saturn, are low. Thus the above discussion is more speculation than firm conclusions.

We conclude that while observational bias is likely not the sole contributor to the imbalance between the already-known numbers of retrograde-to-direct irregular moons observed, it certainly plays some role as a factor that should be taken into consideration. Repeated deep searches close to the gas giants will likely yield more direct moons that have previously escaped detection.

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## Appendix

All of our measurements have been submitted to the Minor Planet Center and can be obtained from Ashton et al. (2021b, https://minorplanetcenter.net/mpec/K21/K21W14.html).

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