

# **Evidence for a Recent Collision in Saturn's Irregular Moon Population**

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# Abstract

Using CFHT imaging data, we searched a 1.1 deg<sup>2</sup> field on each side of Saturn down to magnitude  $m_w \simeq 26.3$ , corresponding to diameters of  $D \simeq 3$  km. We detected 120 objects, which were comoving with Saturn and are nearly certainly irregular moons. For example, all but one of our detections brighter than magnitude 25.5 link to known Saturnian irregulars, with 40 linkages that thus extend the orbital arc of previous discoveries. Extrapolating our sample's characterized detections (those for which we can debias the search) to the entire Saturnian irregular population, we estimate that there are  $150 \pm 30$  moons down to D = 2.8 km, which is approximately three times as many irregular moons as Jupiter down to the same size. At the smallest sizes, from D = 3.8 down to 2.8 km, we find that the Saturnian irregular population exhibits a steep size distribution of the differential power-law index  $q = 4.9^{+0.7}_{-0.6}$ . We believe this steep size distribution is the signature of a relatively recent (few hundred Myr ago) collisional event in Saturn's retrograde irregular population.

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

## 1. Introduction

Irregular moons are eccentric, inclined objects that are found orbiting, usually at many hundreds of planetary radii, around all four giant planets. The moons are thought to be Sun-orbiting planetesimals that were captured by the giant planets during the late stages of planet formation or collisional fragments of them. Nicholson et al. (2008) review several processes that have been suggested for the initial capture mechanism: gas drag, pull down due to sudden mass growth, and three-body interactions (either the planet capturing one member of a passing binary or a planetesimal capture during a planet-planet encounter), although consensus has not yet been reached. Short orbital periods and eccentric orbits, along with the relatively small volume of space occupied by irregular moons, result in collisions significantly altering the initial population of irregular moons into the current size distribution (Bottke et al. 2010). Still, the current orbital and size distributions of irregular moons provide some constraint on capture models and the initial populations (Nicholson et al. 2008; Nesvorný et al. 2014).

Phoebe, discovered in 1898, was the first irregular moon of Saturn to be found. It took over a hundred years to find another Saturnian irregular, which in hindsight is due to the order-ofmagnitude gap in size between Phoebe and the next-largest irregular, Siarnaq. With the use of a wide-field CCD camera, Gladman et al. (2001a) found Siarnaq and 11 more; this study noted that Saturnian irregulars were arranged into three obvious groupings in inclination space. There are two direct clusters, which were named the Gallic and Inuit groups, and a more dispersed retrograde population, all of whose members became known as the Norse group. Both of the direct groups are tightly clustered, with mean inclination ranges of only a few degrees. However, the Norse "group," even at the time, covered a greater inclination range; S/2004 S8 (now Skathi) was

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. separated by  $\approx 20^{\circ}$  and was suggested to not be part of the  $i \simeq 175^{\circ}$  Phoebe cluster; this led Gladman et al. (2001a) to suggest that only the three multimoon clusters were the result of collisional breakups. The only subsequent survey work dedicated to finding Saturnian irregulars, by Scott Sheppard et al., used Subaru to find 45 moons between 2004 and 2007, 21 of which are mentioned in Nicholson et al. (2008), but details of the searches have not been published. Resulting discoveries from this work show that the retrograde inclinations now cover a broad range of about  $30^{\circ}$  and that while Phoebe still probably has a group within a few degrees of its inclination, the overall retrograde moon space has filled out to a large number of moons between Phoebe and Skathi (and slightly beyond), making it clear that the there is no tight clustering in the Norse group, even if a subcluster near Phoebe is evident (Nicholson et al. 2008).

As of early 2019, no new Saturnian irregulars had been discovered, and almost none of the known moons had been imaged, for over 10 yr. Because this is comparable to or longer than some of the observed arcs, the growing orbital uncertainties require further astrometric observations to maintain accurate ephemerides (Jacobson et al. 2012). Currently, there are 58 known Saturnian irregular moons, of which 7 belong to the Inuit group, 5 to the Gallic group, and 46 to the Norse group, 6 of which were considered "lost" at the start of 2019 by Jacobson et al. (2012).

The velocity dispersion over the entire Norse group has the large value of  $650 \text{ m s}^{-1}$  (Turrini et al. 2008), significantly higher than what is thought to be a likely range for fragments from a catastrophic disruption, of  $\sim 100-200 \text{ m s}^{-1}$  (Grav et al. 2003; Nesvorný et al. 2004; Turrini et al. 2008). Although it has been shown that an initial, post-breakup velocity dispersion can subsequently increase over time via gravitational scattering by Phoebe, this process is too ineffective to generate the velocity dispersion of the entire Norse group (Li & Christou 2018). Inward migration of Phoebe over the age of the solar system as that moon steadily swept up the direct population could have decreased Phoebe's *a* to the current value from an initial semimajor axis of order 30% larger (Z. Rogoszinski and



**Figure 1.** Cumulative absolute magnitude functions and diameter distributions of several irregular moon grouping of Saturn, for moons discovered before the work presented in the paper. Phoebe is off the left of the plot. Previously, the irregular moons have been split up into the Inuit group, the Gallic group, and the very dispersed Norse group of all retrograde moons. Here we have chosen to separate a "Phoebe subgroup" (having mean inclinations within 3° of Phoebe's), leaving the rest of the Norse group with all the remaining retrograde moons. The magnitude ranges where we suspect there are small and significant amounts of incompleteness are represented by light and dark gray regions, respectively (see Section 3.5). The top scale shows diameters estimated using an albedo of 0.06.

D. Hamilton 2020, private communication). Thus, the idea that the entire Norse group was produced by a single collision appears unlikely. The next logical hypothesis is that the Norse group is the product of multiple collisional events. Phoebe's large size means it single-handedly holds half of the potential collisions between known Saturnian irregulars (Turrini et al. 2008); the existence of some collisional family involving Phoebe is a plausible event over Gyr time scales. We have taken the approach of dividing the known retrogrades into Phoebe-like orbits and then the rest into the Norse group; we denote the Phoebe-like group as those having mean inclinations within  $3^{\circ}$  of Phoebe's, which is about double the width of the Gallic and Inuit groups. The Phoebe subgroup includes Ymir, Suttungr, Thrymr, Greip, S/2004 S 22, S/2004 S 23, S/2004 S 25, S/2004 S 35, S/2007 S 2, and S/2007 S 3.<sup>1</sup>

Figure 1 shows the luminosity functions (and thus estimated diameter distributions) of these four groupings. Interestingly, while the other three groups show broadly similar distributions down to  $H_V = 15.5$  ( $D \simeq 4$  km), the reduced Norse subgroup lacks any H < 14 members and has a steeper slope. The Phoebe subgroup size distribution ramps up around H = 15.5 to a comparable slope to that of the reduced Norse subgroup. However, we believe there are some missing moons at this size, which will likely slightly alter the slopes. We felt that the steep slopes of both retrograde subgroups could be a sign of a recent

collision and wanted to ensure that the apparent slope is accurate and extend it to smaller diameters. Figure 1 also makes it abundantly clear that the Saturnian irregular population is dominated by retrograde moons, and more specifically the reduced Norse subgroup. To our knowledge, this has not been previously mentioned in the literature. If the current slopes of the size distributions of the groups continue to smaller sizes, then the disparity will only increase.

Phoebe's small semimajor axis and eccentricity, compared with the other Norse group members, mean that the removal of Phoebe from the Norse group decreases the group's velocity dispersion from 658 m s<sup>-1</sup> down to 315 m s<sup>-1</sup> (Turrini et al. 2008). Thus, removing the Phoebe-like moons in our reduced Norse subgroup will reduce this value down to roughly  $300 \text{ m s}^{-1}$ , which is now closer to reasonable catastrophic disruption breakup dispersion speeds (for reference, Phoebe's surface escape speed is ~100 m s<sup>-1</sup>). The still-high velocity dispersion and large inclination range suggest that the reduced Norse group could be subdivided further.

The four largest moons ( $H_V < 14.5$ ) in the reduced Norse group have roughly the same size, however, which is an unusual outcome in asteroid belt collisional families. Perhaps subsequent collisions could explain this. The luminosity functions of the Phoebe-like moons and the two direct groups are much shallower down to 5 km, suggesting that these objects are either originally captured moons from a shallow size distribution, or they were formed from a collision long ago and enough time has passed to grind down the size distribution.

 $<sup>\</sup>frac{1}{1}$  S/2007 S 3 only has a 90 day arc and thus its membership in the Phoebe subgroup is uncertain. Unlike Nicholson et al. (2008), we do not place Fornjot = S/2004 S8, with mean  $i \simeq 170^{\circ}$ , in the Phoebe subgroup.



Figure 2. The position of our two fields relative to Saturn (red dot). The fields are broken up into each CCD and are color-coded depending on which sky brightness region they belong to. Predicted 2 month arcs of known moons are shown (blue/magenta dash lines, with blue being chronologically first) starting from the night of the first observations (2019 July 1); a black arrow is added to the bottom-most known moon to show the direction of motion of that moon. Black dots indicate the position of all of our detections (after removing matches to implanted signals). The outer black dashed line represents a circle with a radius of half a Saturn Hill radius, within which all the previously known moons were projected to be.

Irregular moons, like other small-body populations, have size distributions that appear to obey a power law:  $N(D)dD \propto D^{-q}dD$ , where *D* is the diameter of the moon, N(D)dD is the number of moons that have radii between *D* and D + dD, and *q* is the differential power index. The size distribution of Saturnians, along with the other three giant planet irregular populations, has a shallow slope for their largest members, with  $q \approx 2$  for 200 > D > 20 km (Nicholson et al. 2008). For small irregular moons, the slope of the size distribution near the limit, for both Saturnians and Jovians, appears to steepen with q > 3.5 for D < 10 km (Nicholson et al. 2008).

The main motivation for this project was to determine if the steep slope in the luminosity function continues down to fainter moons, as well as reimaging a majority of the moons that were considered to be in danger of being lost. The breakdown of this paper is as follows: Section 2 details the data set and our method for finding Saturnian irregular moons, and Section 3 describes how we produced our size distribution and subsequent analysis.

# 2. Current Data Set and Reduction Methods

The data set consisted of two 1.1 deg<sup>2</sup> Canada–France– Hawaii Telescope (CFHT) MegaPrime fields. The two fields were directly east and west of Saturn, with the side closest to Saturn only 7' away from the planet (see Figure 2). Both fields were visited on consecutive nights; the east field on July 1 and 2, and the west field on 2019 July 3 and 4 (UT). Each visit consisted of 44 sequential 205 s exposures. Including the 40 s CCD readout time, each visit lasted 3 hr. The single exposure time was limited by Saturn's on-sky motion of 11'' hr<sup>-1</sup>; longer exposures would lead to mild trailing due to the motion of the moons in median 0."7 seeing conditions.

All images were unbinned, with a 0."186 per pixel scale, and were acquired using the *gri* filter. The *gri* filter, which we will

refer to as the *w* filter for the remainder of the paper, has a wide bandpass that is similar to the Sloan *g*, *r*, and *i* filters combined.

For each field, the night with the poorer image quality (of the two) was chosen for the "characterized search." This was done so moons that were discovered on the characterized night will be above the magnitude limit of the uncharacterized night and thus easily redetected. The first east field night (July 1) had worse seeing compared to the second (and the two west field nights). The two west field nights had similar seeing, with the second night (July 4) slightly the worse of the two. Thus, characterized searches were performed on the 1st (east) and 4th (west) of July images. The average seeing was  $\sim 0.77$  for the 1st of July and  $\sim 0.76$  for the other three nights. Standard preprocessing was done by the Canadian Astronomy Data Centre's CFHT MegaPrime pipeline.

For the characterized nights, the order of image processing was as follows: all images were aligned to the first image of the sequence; artificial moving objects were implanted in each image (details in next paragraph); the images were flux scaled relative to reference stars in the first image; and a  $25 \times 25$  pixel-size boxcar filter was then applied to background subtract the images. For details on these processes, see Gladman et al. (2001b). The image processing for the uncharacterized nights was exactly the same as that of the characterized night except no artificial objects were implanted.

Artificial moons were randomly implanted into the images in order to determine our efficiency at finding moons. The number of moons implanted in each CCD ranged from 150 to 160. The magnitude, on-sky rate, and position  $angle^2$  (PA) of the implanted moons were drawn from a uniform distribution ranging from 24.5–27.0, 54–66 pix hr<sup>-1</sup>, and 258°–266°

 $<sup>^2</sup>$  Here, PA is the direction of the motion of an object measured anticlockwise from direct north.

respectively. The rate and PA ranges were chosen to go slightly beyond the minimum and maximum values for all known Saturnian irregulars. Parts of the CCDs where we knew that the fastest moon would move off the CCD during the 3 hr sequence did not have any moons implanted in them, as this was also how the frames would be later trimmed after shifting. Details of the implanted moons were unknown to the human operators until after the search was completed.

Once these processing stages were complete, the 44 image set was shifted at a grid of different rates and PAs and then combined using the median value at each pixel. This method is quite effective at minimizing stellar confusion when moons move in front of them over the exposure sequence. To remove the effect of cosmic rays or bad pixels and to further lessen the presence of stars, we rejected the three highest and one lowest values for each pixel while combining the images, based on experience (Gladman et al. 2001b). For the characterized nights, we created a grid of different shift rates and PAs. The range of shift rates goes slightly beyond the implanted rate range (53 to 67 pix  $hr^{-1}$ ), and the range of shift PAs was chosen to be the same as the implanted PA range  $(258^{\circ}-266^{\circ})$ . Using step sizes of 2 pix  $hr^{-1}$  and 2° produced five different shift PAs and eight different shift rates, with a total of  $5 \times 8 = 40$  different recombinations. We trimmed away from the stacked images any stacked pixel that would have resulted in a moon starting on that pixel leaving a field over the 3 hr sequence. This procedure produced 40 adjacent "mini-fields" for each field in our search and meant we were able to search about 90% of the original sky area.

All rates and PAs were searched methodically by two human operators using a five-rate blinking sequence. The two different rate sequences chosen were [53, 55, 57, 59, 61] pix  $hr^{-1}$  and [59, 61, 63, 65, 67] pix  $hr^{-1}$ , which easily covered the rate range of the known Saturnian irregulars and allowed overlap between the two sequences. By blinking multiple rates at a time, moons can be easily identified by their characteristic pattern of coming in and out of "focus" as the recombination rate and PA gets closer and further from the moons' actual rate and PA. Initially, each CCD was searched by both operators. After searching three CCDs, the detections of the two operators were deemed similar enough that, in order to save time, only one operator searched subsequent CCDs.

The two uncharacterized nights were not searched in this methodical fashion. Images from these nights were only shifted and stacked at rates and PAs that were needed to redetect (track) the moons that were found on the characterized nights. Because we chose to characterize the poorer-seeing night, this resulted in the (intended effect of) recovery on the second night of all but one of the moon candidates from the characterized night at locations expected for objects comoving with Saturn (see Section 3.2).

#### 3. Results

#### 3.1. Detection Efficiency

After a given CCD had been fully searched, all the moving objects that were detected were compared with the list of implanted moons. An implanted object was labeled "found" when it was matched (within a tight tolerance) to a detection. Any object found that was unable to be matched to an implanted object became a candidate moon.

The close proximity of the fields to Saturn meant that scattered light from the planet produced a substantial gradient in the sky brightness across both fields. We acquired test exposures in early 2019 at various offsets from the planet and determined that a 7' spacing between the planet and the closest edge of the Megaprime mosaic field minimized overall sky levels and internal reflections while keeping as close to Saturn as possible. The sky brightness gradient causes the detection efficiency to vary across a field, arguing against using a single detection efficiency function. To remedy this, the CCDs of both fields were divided into regions with similar measured sky background levels, and the efficiency function was obtained for each region. Each field contains four regions, named, in order of increasing sky brightness, "dark," "mid," "bright," and "brightest." The CCDs are color-coded in Figure 2 to indicate which region they belong to.

To obtain the efficiency functions, the fraction of implanted objects found in a particular region was binned and then fit with a hyperbolic tangent function:

$$\eta(m_w) = \frac{A}{2} \left( 1 - \tanh\left[\frac{m_w - \mu}{\delta}\right] \right) \tag{1}$$

where  $A \simeq 1$  is the fraction of bright objects that are detected,  $\mu$  is the magnitude where the fraction drops to  $A/2 \simeq 0.5$ , and  $\delta$  is the "width" of the drop. Figure 3 shows the curve of best fit for the eight different regions. For the size distribution study, we term the "characterization limit" to be where the detection efficiency drops to 0.5. Therefore, our characterization limit varies from  $m_w = 25.9$  to 26.4, depending on the region. The characterization limit for each region is indicated by a dotted line in Figure 3. Despite a typical moving source's path crossing several background galaxies, stellar halos, and/or badpixel columns, essentially all sources brighter than 25th magnitude were easily recovered. The east regions have brighter limits compared to their west counterparts because of the seeing difference between the fields.

The fraction of implanted moons that were found as a function of rate and PA is essentially constant. Thus, a moon's rate and PA do not need to be considered when it is debiased.

#### 3.2. Detections

Our search generated 120 moon candidates. The original unimplanted images were recombined using the average pixel values to obtain astrometry (relative to the USNO catalog) and aperture photometry measurements for all of the detections. The position, relative to Saturn, of these candidates are shown in Figure 2 as black dots, with more near the planet, similar to previously known moons. Of these 120, 93 candidates were found in the characterized search, with 74 of those having magnitudes above the characterization limit of the region where they were found in. These 74 will be known as characterized detections, and Tables 1 and 2 contain a list of these objects found in the east and west fields, respectively. The 19 candidates found during the characterized night, but which had magnitudes below the region characterization limit, are listed in Table 3.

All but 1 of the 93 candidates that were found on the characterized night were easily found on the adjacent betterseeing uncharacterized night, and are thus real. This one object, w13r59a7, is roughly 27th magnitude (well below the CCD's



Figure 3. Efficiency functions of our eight different sky brightness regions (see Figure 2) obtained by fitting the fraction of implanted moons that were found in each region. The magnitude where each function drops to 50% is indicated by a vertical dotted line of the same color.

50% completeness magnitude of  $m_w = 26.4$ , and thus an uncharacterized detection) and is obscured by multiple stars at its projected position on the adjacent uncharacterized night.

The uncharacterized nights yielded an extra 27 candidates (listed in Table 4): 3 from targeted searches of known moons (see Section 3.3 for more details) and 24 from a quick search. The quick search consisted of a single rate sequence close to Saturn's rate and PA to find moons that were missed during the characterized search. Five of the 24 quick search detections had magnitudes that would have been found almost 100% of the time on the characterized night (according to the efficiency function of the CCD they would have been found on), so why were they not found during the characterized search? Two of them were at locations trimmed out of the shift-and-stack search area and thus could not be found during the characterized search (Skathi and x20r61a8). The other three were on the search area but obscured by bright stars (f29r60a8, f35r57a9, and S/2004 S 30).

Note that "uncharacterized detections" are those that cannot be debiased with an estimated detections efficiency; we use this term for both detections in the characterized night that are beyond the CCD's 50% detection efficiency (because we do not believe we can reliably estimate  $\eta(m_w)$  for  $\eta < 50\%$ ) and for moons found in the search of the uncharacterized night (for which the detection efficiency is not measured).

Of the seven detections that were found during the search of the uncharacterized west night (see the "x" designations in Table 4), four of them were not found when we went back to search for them in the characterized night; in two of those cases the object had moved off the search area on the characterized

night. In contrast, 8 out of 17 of the equivalent east field detections were found only on the uncharacterized night, all of which should have been in the search area. This large number of objects found only on the uncharacterized east night is due to the large disparity in the seeing between the two east nights.

# 3.3. Linking to Known Moons

The Minor Planet Center (MPC) Natural Satellite Ephemeris Service predicted that 42 known moons, which were not considered lost, should be inside the outer boundaries of our fields. Of those 42, 34 (81%) were linked to objects found during the characterized search. Our 81% detection efficiency at finding known moons is consistent with 84% of our field being searchable (7% percent of our field is lost due to chip gaps, then 10% of the remaining field is lost due to trimming). Three of the eight known moons not found during the characterized search were linked to a candidate found on the uncharacterized night. We did a targeted search for the remaining five known moons in our field and three (see Table 4) were found in the untrimmed data, thus leaving the CCDs. One of the known moons that was never found, S/2006S 1, was predicted to be in a large chip gap on both nights, as such, we had no chance of finding it. The remaining moon that was never found, S/2004 S 37, should have been found if it were at its predicted position. Thus it is likely slightly off the predicted position and in a nearby chip gap. Better accuracy in the predicted position may help us find S/2004 S 37 in our images.

 Table 1

 A List of Characterized Detections in the East Field (2019 July 1)

Our Designation	Known Designation	m <sub>w</sub>
e05r56a6	Paaliaq (XX)	21.6
e26r63a6	Erriapus (XXVIII)	23.4
e29r59a9	S/2004 S 32	24.9
e15r57a10	S/2004 S 25	25.1
e26r58a12		25.1
e10r59a8	Greip (LI)	25.3
e24r57a7	Skoll (XLVII)	25.4
e37r57a10	Fenrir (XLI)	25.5
e35r56a8		25.7
e16r57a10		25.7
e13r57a8	S/2004 S 23	25.8
e11r60a10		25.8
e16r62a8		25.8
e02r59a08		25.9
e21r57a8		26.0
e15r61a8s	S/2004 S 12 <sup>a</sup>	26.1
e03r61a10	S/2004 S 21	26.1
e10r59a9		26.1
e12r58a8		26.1
e23r61a6		26.1
e02r59a10	Farbauti (XL)	26.2
e11r59a8		26.2
e21r63a8		26.3
e31r62a6		26.3

**Note.** We give our internal designation, the MPC designation if it is previously known, and the moon's *w*-band magnitude. Our designations start with an "e" (for east) followed by the CCD number the moon was found on, then an "r" (for rate), followed by the rate (in pixels  $hr^{-1}$ ) that gave the best recombination, then an "a" (for angle), and lastly the angle (in degrees) that gave the best recombination. Note: the angle we use here is not the PA but 270° minus the PA.

 $^{a}$  S/2004 S 12 was  $\sim$ 5' away from its predicted position but the linkage was confirmed via private communication with Gareth Williams.

There are four Saturnians with provisional designations that are lost: S/2004 S 7, S/2004 S 17, S/2004 S 13, and S/2007 S3. All four of these moons, due to the few-month arcs from 2004-2007, have enormous ephemeris errors at the time of our observations (of order thousands of arcseconds according to the analysis of Jacobson et al. 2012). It is possible that these moons are actually among our detections, but linkages to the lost moons have yet to be tested.

Although there are hundreds of bright (visible on single images) asteroids in our fields, all 14 objects with  $m_w < 25.1$  that were in the fields and in our rate range have been easily linked to known moons. We believe that if main belt asteroids were generating any significant confusion into the rate cut, it is highly likely some of them would have been bright, given how shallow the main belt luminosity function is at these magnitudes (off of opposition, this can become a serious contamination issue but is not a problem here). While there remains a small possibility that one of these detections happens to be a small Centaur passing close to Saturn, an interloper will have a negligible effect on our analysis of the size distribution of Saturnian irregulars.

#### 3.4. Converting to Radii

To compare our detections with the irregular moon populations of other planets, we converted our measured magnitudes into rough diameters. Using the assumption that all the irregular moons of Saturn have the same albedo and are at

 Table 2

 A List of the Characterized Detections in the West Field (2019 July 4)

Our Designation	Known Designation	m <sub>w</sub>
w19r63a6	Phoebe (IX)	16 <sup>a</sup>
w36r57a8	Ymir (XIX)	22.2
w28r57a10	Kiviuq (XXIV)	22.3
w38r63a3	Ijiraq (XXII)	23.2
w20r61a7n	Suttungr (XXIII)	24.5
w20r61a8s	Mundilfari (XXV)	24.5
w25r61a6	Narvi (XXXI)	24.6
w19r61a4	Bebhionn (XXXVII)	24.6
w36r63a6	Kari (XLV)	24.6
w20r61a7s	S/2007 S 02	25.0
w24r59a9	Loge (XLVI)	25.1
w10r58a6	Aegir (XXXVI)	25.2
w38r58r6	S/2004 S 27	25.2
w19r63a8	S/2004 S 35	25.2
w22r59a8	Hati (XLIII)	25.3
w10r62a7	S/2004 S 26	25.4
w14r59a8s	Fornjot (XLII)	25.5
w19r57a5	S/2004 S 38	25.5
w09r65a4	S/2004 S 29	25.6
w26r62a6	s/2006 S 03	25.7
w13r61a8	S/2004 S 20	25.7
w03r61a5		25.7
w02r59r8		25.8
w11r62a7		25.8
w13r63a8		25.8
w04r59a9		25.9
w32r59a8		25.9
w38r57a3		25.9
w08r59a6		26.0
w14r61a8		26.0
w25r59a7		26.0
w36r53a4		26.0
w39a61r8		26.1
w14r59a8s		26.1
w13r59a8a		26.1
w10r63a6	S/2004 S 34	26.2
w33r60a7		26.2
w09r65a6		26.2
w19r57a8		26.2
w02r60a8		26.2
w23r60a8		26.2
w22r61a6		26.2
w14r58a8		26.2
w09r57a9		26.3
w15r61a6		26.3
w20r61a8n		26.3
w18r63a10		26.3
w24r61a7		26.3
w31r59a8		26.4
w02r57a10		26.4

**Notes.** See Table 1 for details, with the exception of the starting character for our designations: "w" for west, instead of "e."

<sup>a</sup> We were unable to get accurate photometry due to Phoebe being saturated on single exposures and thus assigned it an approximate magnitude.

the same distance from Earth during our observations, then the apparent magnitude m of a moon provides a diameter D using the simple relation:

$$D = 10^{(m_1 - m)/5} \text{ km}, \tag{2}$$

where  $m_1$  is the magnitude of a moon with a diameter of 1 km. To obtain  $m_1$  for the *w* band (which we will refer to as  $m_{1w}$ ) we

Table 3

A List of All Uncharacterized Discovery-night Detections (That Is, Found during the Characterized Search but below the 50% Detection Efficiency for That CCD)

Our Designation	Known Designation/Comment	$m_w$
e37r62a8	S/2004 S 33	26.0
e37r55a10		26.0
e15r61a8n		26.3
e16r63a8		26.3
e17r61a8		26.4
e08r57a10		26.5
e14r59a6		26.7
e23r59a11		26.9
w38r62a7		26.4
w38r62a8		26.5
w24r58a8		26.5
w09r55a7		$\sim 26.5$
w15r58a8		$\sim 26.5$
w24r61a8		26.6
w13r59a8b		26.6
w25r61a9		$\sim 27$
w13r59a7	1 night	${\sim}27$
w09r63a6		$\sim 27$
w12r63a6		$\sim 27$

**Note.** Unless noted, these are two night detections. See Table 1 caption for details. In some cases where photometry could not be performed accurately, these candidates are indicated by  $a \sim$  before their magnitude.

fitted the above relation using a moon's  $m_w$  measured in this work and D in Table 4 in Grav & Bauer (2007). Using the nine moons that have both a measured  $m_w$  and a Grav & Bauer (2007) D, we get a w-band  $m_{1w} = 28.6$  (Figure 4), which we adopted as our calibrated value. Because we do not know whether the moons are in front of or behind Saturn, the uncertainty in the moon's geocentric distance would be  $\pm \frac{1}{2}R_H$ , with a corresponding uncertainty in  $m_{1w}$  of  $\pm 0.1$ .

To be able to compare our results with the previously known population of Saturnian irregulars, we also obtained diameters of all previously known Saturnians by performing the same fit using the predicted  $m_V$  values obtained from the MPC for our nights of observation. Using the 12 moons that have both an MPC  $m_V$  and a Grav & Bauer (2007) D, we get for the V-band  $m_{1V} = 28.7$  (Figure 4), allowing us to estimate the previous completeness in the next section.

Along with the size conversion, Figure 4 also shows the cumulative number of candidates found during the characterized search (green diamonds). An exponential curve with  $\alpha = 0.5$  (corresponding to collisional equilibrium; Dohnanyi 1969) is added for reference (black curve). Beyond magnitude 24.5, the numbers increase roughly exponentially. Even without debiasing these detections (which will only increase the number of moons near the limit), one can see that Saturnian irregulars are steeper than collisional equilibrium.

#### 3.5. Population Estimate

To debias the characterized detections, we weighted each by the detection efficiency in their region. Each detection contributes  $1/\eta(m_w)$  detections to the absolute magnitude distribution, where  $\eta$  is the regional detection efficiency at the object's measured magnitude (Adams et al. 2014).

The variability of the efficiency function slightly complicates this simple method of constructing a debiased size distribution. One would want to use all regions of our fields to include as many moons as possible in our size distribution. However, the size distribution can only go as deep as the characterization limit of the shallowest region, and thus including the regions with more scattered light results in the size distribution not going as deep as it could. As such, we have decided to create two debiased size distributions: one using the whole two fields but only going down to  $m_w = 25.9$  (the shallowest CCDs; see Figure 2) and a second using only our four deepest regions but going down to  $m_w = 26.3$ . We shall refer to the two size distributions as "shallow" and "deep," respectively. The four deepest regions are east dark, west bright, mid, and dark. The number of characterized candidates used for the "shallow" and "deep" size distributions is 42 and 53, respectively.

To obtain an estimate, using our detections, of the total number of Saturnian irregulars present in Saturn's Hill sphere, we need to know the fraction of the entire population in the Saturnian offset of our fields. Because the two samples cover different regions of our fields, we need two different fractions. Thus, we split our fields into individual CCD subfields, producing 80 subfields each with their own offset from Saturn. We counted the number of known moons in each subfield, with the same on-sky offset from Saturn as our data, for 10 different oppositions (2014 to 2023). We only count the moons that land on a CCD that belongs in a region used in a sample, and then we averaged the number of moons over the 10 different oppositions. Note that over this 10 yr time interval the moons complete many orbits and thus "lose memory" of where they were discovered (all moons were discovered before 2008). This process yields that, on average, 41 (of the total 58) known moons are in the offsets used in the "shallow" sample and 28 known moons in the less extensive "deep" regions. These numbers drop to 37 and 25, respectively, when we take into account the 10% sky area loss due to trimming (the CCD gaps were already accounted for by splitting into subfields). Thus, the multipliers going from our "shallow" and "deep" samples to the full populations is  $1.6 \pm 0.2$  (58/37) and  $2.3 \pm 0.3$  (58/25), respectively; the uncertainty values come from the standard deviation of the number of known moons over the 10 oppositions.

Both of our total population estimates overlap nicely with the known population (see Figure 5) down to  $D \simeq 4$  km. There are a few ranges where our estimates deviate from the known population, but this deviation is not significant until  $m_w = 25.8$ (D = 3.5 km), after which point the known population rolls over and diverges from our debiased estimate. This discrepancy is certainly due to the expected incompleteness of the known moons starting at this magnitude. We have several objects brighter than  $m_w = 25.8$  that are yet to be linked to known moons, with the brightest being  $m_w = 25.1$  (D = 5 km). Thus, we conclude that the irregular moons of Saturn are very likely fully complete down to D = 5 km and nearly fully complete down to D = 3.5 km, with the completeness significantly deteriorating beyond this diameter.

Using the deep sample, we estimate there are  $150 \pm 30$ Saturnian irregulars down to D = 2.8 km ( $m_w = 26.3$ ). Thus, there are approximately three times as many Saturnian irregulars as Jovian irregulars down to this size (Ashton et al. 2020). Due to the Saturnian size distribution being steeper compared to that of Jovian size distribution, at  $D \simeq 3$  km (see

Our Designation	Known Designation	$m_w$	Comment
	Thrymr (XXX)	24.2	Near CCD edge.
	Surtur (XLVIII)	25.8	Near CCD edge.
	S/2004 S 22	26.0	Near CCD edge.
f24r59a10	Skathi (XXVII)	24.4	Off trimmed area in charac night.
f29r60a8		25.3	In multiple bright stars in charac night.
f35r57a9		25.4	Close to saturated star in charac night.
x20r61a8		25.6	Off trimmed area in charac night.
f37r55a8		25.7	Only found on uncharac night.
x13r61a6	S/2004 S 30	25.8	Close to saturated star in charac night.
x19r63a8	S/2004 S 28	$\sim 26$	Near CCD edge, 2' off prediction.
f24r62a8		26.0	Only found on uncharac night.
f20r59a8		26.1	In bright star in charac night.
f22r59a8n		26.1	Close to saturated star in charac night.
f03r56a9		26.2	-
x14r57a7		26.3	In chip gap in charac night.
x19r59a4		26.3	Only found on uncharac night.
x28r63a8		26.4	
f14r54a7		26.4	Only found on uncharac night.
f22r59a8s		26.4	Only found on uncharac night.
f39r57a13		$\sim 26.5$	
x18r57a6		26.5	
f39r59a8		26.5	
f16r59a8		26.6	
f11r59a6		$\sim 27$	Only found on uncharac night.
f17r63a8		~27	Only found on uncharac night.
f22r57a9		$\sim 27$	
f39r57a8		$\sim 27$	Only found on uncharac night.

 Table 4

 Additional Objects Detected in Our Data Set

Note. These were either known moons not in the full-depth stack area (and are thus not part of the characterized survey), or objects that were serendipitously detected when examining the uncharacterized night. See text for discussion. See the Table 1 caption for column contents, with the change that here f = detections in the east field and x are detections in the west field.

Section 3.6), this disparity will likely only increase for smaller moons.

immediately implies that the size distribution must be very steep near  $D \simeq 3-4$  km.

#### 3.6. Slope of Debiased Luminosity Function

We performed a single power-law least-squares fit on the cumulative size distribution of debiased deep detections from D = 3.8 km down to 2.8 km ( $m_w = 25.7-26.3$ ). The large number of detections we find makes it obvious that the size distribution must be very steep; the resulting differential power-law index we find is large, with  $q = 4.9^{+0.7}_{-0.6}$ . The uncertainties were obtained by randomly drawing diameter values, ranging between 2.8 and 3.8 km, from a power-law distribution with q = 4.9 until we had the same number of values as samples in the size range. This was repeated for 100,000 simulated samples for which we fit a power law to the simulated size distribution, thus producing a distribution of q values. We identified the two q values that, between it and the median value, contained 34% of all q values above and below, and chose it as our uncertainty bounds.

Our q = 4.9 value is significantly larger than the standard value for collisional equilibrium, q = 3.5 (Dohnanyi 1969). Repeating the method above, assuming the true distribution had q = 3.5, demonstrated that the size distribution derived from another 100,000 samples produced a slope with  $q \ge 4.9$  less than 1% of the time (see Figure 6). We thus conclude that the size distribution of Saturnian irregulars in the size range of D = 3.8 km down to 2.8 km is significantly steeper than collisional equilibrium. The very fact that the great majority of our detections are in the last magnitude (see Figure 4)

## 4. Discussion and Conclusion

We hypothesize that the steep Saturnian size distribution, from D = 4 km down to 3 km, is a signature of a significant "recent" collision (or collisions) in its irregular moon system. Size distributions with  $q \simeq 5$  are seen in asteroid belt families that are interpreted (Parker et al. 2008) as the aftermath of either catastrophic parent-body breakups (in which case the largest remaining fragments tend to be of comparable sizes) or major cratering events (where the surviving parent body is much larger than the next-largest family member, but the fragments then have a steep size distribution). The argument for recency (see below for estimates of the timescale) is because mutual collisions should subsequently grind down the initially steep size distribution toward an equilibrium value of  $q \simeq 3.5$ , as seems to have occurred at Jupiter (Figure 5 and Bottke et al. 2010; Ashton et al. 2020).

The situation at Saturn appears quite complicated, however. The most obvious explanation seems clearly wrong; as discussed in the Introduction, the entire retrograde group has a velocity dispersion too large to plausibly be explained as a simple cratering event off of Phoebe. Both the inclination and semimajor axis distributions of the retrograde moons are not easily explainable with a velocity field of a collision off of Phoebe. On the other hand, it would be hard to imagine that Phoebe has not been involved in large collisional events, as its



Figure 4. The relationship between a moon's magnitude and diameter (left scale) and the cumulative number of detections found during the characterized search to a *w* magnitude of 26.4 (right scale). The magnitudes are either our *w*-band measurements (blue squares) or *V*-band measurements obtained from the MPC (red circles). Note: moons that have both *w* and *V* magnitudes appear twice. Diameters were taken from Grav & Bauer (2007). The best-fit exponential for both sets of magnitudes are included (dashed lines). The cumulative number of candidates detected during the characterized search (as a function of *w*-band magnitudes) is shown as green diamonds. An exponential curve with  $\alpha = 0.5$  is added for comparison (black line).

much larger size means it hosts as much cross section as the sum of all other known moons (Nesvorný et al. 2003; Turrini et al. 2008). The moons that we identify as in the "Phoebe subgroup," with mean inclinations within 3° of Phoebe, are plausibly ejecta from a very large cratering event on Phoebe. As predicted in Gladman et al. (2001a), Phoebe does have very large impact structures (the  $D \simeq 100$  km impact craters Jason and Eurytus later discovered during the Cassini flyby). These craters are of the scale to be formed by impactors the size of the largest (5-20 km) surviving moons, and it is plausible that Phoebe has produced cratering ejecta with velocity dispersion of a few times its escape speed (especially if the impactor was from the direct moons with a relative impact speed of order twice the orbital speed). The high crater density on top of Jason and Eurytus (the largest of which is Erginus, with  $D \simeq 40 \text{ km}$ ) suggests that the largest craters are not recently formed.

In the remaining retrogrades not in the Phoebe subgroup, Figure 1 shows that there are no D > 10 km moons surviving to the present day. Steady mutual destruction of irregular moons over 4 Gyr is an expected outcome due to the small volume they occupy (Bottke et al. 2010), and in fact, that study finds that the

survival of Phoebe itself is a rare outcome. We therefore suggest the plausible scenario that the recent breakup is related to a nowdestroyed retrograde moon, whose fragments make up most or all of the abundant D < 10 km retrogrades outside of the Phoebe subgroup. It is also reasonable that after an initial large breakup creating a steep size distribution, there have been additional catastrophic fragmentations in the population, producing the observed subclumps (e.g., Denk et al. 2018) and spreading the retrogrades even more in inclination. This "short-term collisional cascade" would also potentially break up intermediate scale moons in the Phoebe subgroup, providing an avenue to explain why Phoebe's subgroup below 5 km (see Figure 1) may also be showing a steep size distribution, as Phoebe-group moons comparable to Suttungr ( $D \simeq 8$  km) were broken up by projectiles now loose in the system. Piecing together clues to this story would be aided by having orbits of all the new moons discovered in this work. Our study demonstrates that below 4 km, the size distribution becomes even steeper (Figure 1) than the previously known moons showed at the previous incomplete limit (Figure 5). To know for sure which group (or subgroup) these abundant  $D < 4 \,\mathrm{km}$  moons belong to, their orbits will need to be



**Figure 5.** A comparison of our two debiased Saturnian size distributions estimates, shallow (red) and deep (green), with that of previously known Saturnian irregulars (black). These estimates are the number of moons in the entire irregular population, not just in our fields; the shaded areas represent the estimated uncertainty range. For comparison, we show the debiased estimate for retrograde Jovian irregulars (blue) from Ashton et al. (2020) down to  $D \simeq 1$  km; smaller than  $D \simeq 3$  km, the Jovian systematic uncertainty is  $\approx$ 50%. A dotted line with a slope of differential q = 3.5 is shown for reference. The Saturnian numbers are increasing steeply relative to both this reference slope and the Jovian moons at a diameter of 3 km.

determined, but such a determination requires roughly five times as much telescope time as we used in the detection. If and when future deep work at Saturn rediscovers these moons, linkages to our two night arcs will be feasible.

To get an estimate of how recent the collision(s) has (have) to be, we use a simple  $n\sigma v_{rel}$  collision rate estimate to find out how long it would take to affect the 4 > D > 3 km moons. Here, *n* is the number density of impactors,  $\sigma$  is the collisional cross section, and  $v_{rel}$  is the relative velocity between impactors and target. We approximate the moons to be spherical, so  $\sigma = \pi r_m^2$ , where  $r_m$  is the mutual radius of the impactors and target, and assume that the impactors have similar semimajor axes and eccentricities to those of the known Saturnian irregulars, with  $a \sim 2 \times 10^7$  km,  $e \sim 0.3$ , and apocenter  $Q \simeq 2.5 \times 10^7$  km. We will assume that the majority of the  $\simeq 100 D > 3$  km moons present in the system are in the non-Phoebe-like retrogrades (as is true for the previously known sample), and thus have mutual inclinations  $\delta i$  of  $\approx 20^\circ$ . We approximate the volume occupied by impactors as a cylinder with a radius of Q and height Q  $\tan(\delta i)$ . Roughly, the relative velocity<sup>3</sup> is  $v_{rel} = v_c \sqrt{e^2 + (\delta i)^2}$ , where  $v_c$  is the circular orbital speed at a distance *a* from Saturn. The collision timescale (inverse of the collision rate) can be estimated as

$$t \sim \frac{Q^3 \tan(\delta i)}{N r_m^2 v_c \sqrt{e^2 + (\delta i)^2}},\tag{3}$$

where N is the total number of impactors.

First we estimate how long it would take the moons between 4 km > D > 3 km to mutually collide. We measure a population (see Figure 5) of  $N \simeq 100$  moons in this size range. Taking  $r_m = 3$  km, the collisional timescale t = 320 Gyr, which is well beyond the age of the solar system. These moons are thus not destroying each other, but in a steep size distribution, one expects the vastly more numerous smaller moons to be the likely dominant catastrophic projectiles. We look at two scenarios, which are likely the two extremes. The first scenario is that the steep q = 4.9 exponent continues down to D = 0.3 km, which is approximately the smallest projectile able to catastrophically destroy a  $D \sim 3$  km moon. This results in  $N \sim 800,000$  impactors and, taking  $r_m = 1.8$  km, gives a timescale of only 0.1 Gyr. If instead the slope of the size distribution drops immediately at our D = 3 km limit to that of collisional equilibrium, q = 3.5, there are only  $N \sim 30,000$ impactors, with a resultant timescale of 2.8 Gyr. The truth is nearly certainly somewhere between these two cases, and we

<sup>&</sup>lt;sup>3</sup> This equation is an approximation for low e and i orbits, so the true relative velocity will be somewhat higher; this approach loses the enhancement in collision rates that occur when mutual i becomes very small or when orbits share peri- or apocenter distances; see Kessler (1981), Nesvorný et al. (2003), and Rickman et al. (2014). These more detailed approaches are not adapted to our purposes because most of the orbits are unknown.



Figure 6. A histogram of the measured slopes of the size distribution derived from 100,000 simulated samples. The diameter of the simulated objects was drawn randomly from a power-law distribution with q = 3.5. Each sample contains the same number of objects as we estimate in the D = 3.8 to 2.8 km range. The vertical dashed line represents the measured value of q = 4.9 from our debiased detections. Only 0.6% of the simulations had a measured slope greater than q = 4.9, indicating that, at >99% confidence, small Saturnian irregular moons have a slope steeper than collisional equilibrium.

weakly bracket the recency of the production of these fragments between 0.1 and 2.8 Gyr. Clearly much more detailed work could be done with precise orbits for the moons.

Another collision possibility for 3–4 km-sized moons involves Phoebe. With  $r_m \sim 100$  km (the size of Phoebe) and  $N \simeq 100$  the timescale of a collision with Phoebe is every ~0.5 Gyr (Phoebe is close enough in inclination to the reduced Norse subgroup that we keep  $\delta i \approx 20^{\circ}$ ). Thus, even without extrapolating to smaller sizes, we can see that the Saturnian irregular population is still collisionally active.

The final aspect of the puzzle is the outermost ring of Saturn, known as the Phoebe ring. The ring particles are believed to be ultimately derived from the ring's namesake, the moon Phoebe. Hamilton et al. (2015) found, however, that the Phoebe ring extends well beyond what a dust ring from Phoebe alone could produce, thus putting into doubt whether Phoebe is the sole direct contributor to the ring; many smaller moons with Phoebe-like inclinations but larger semimajor axes is a potential solution. This result from Hamilton et al. (2015) suggests that perhaps our newly discovered moons are dominated by Phoebe subgroup members. However, of the 18 known moons with diameters between 3 to 4 km, only 3 of them are in the Phoebe subgroup. In contrast, 13 of the 18 are in the reduced Norse subgroup. Thus the q = 4.9 slope is likely due to reduced Norse subgroup members, although orbits of these moons are needed to know for sure. Nevertheless, even if the D < 4 km moons are dominated by reduced Norse subgroup members, there could still be hundreds of kilometer-sized members at distances that range beyond Phoebe's apocenter that dominate the dust supply into Phoebe's ring.

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### Appendix

All of our measurements have been submitted to the MPC but anyone who wants a copy of the astrometry files can request them from the authors.

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