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Classification of F ring features observed in Cassini UVIS occultations

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Abstract

The Cassini Ultraviolet Imaging Spectrograph (UVIS) has detected 27 statistically significant features in 101 occultations by Saturn’s F ring since July 2004. This work nearly doubles the number of features reported by Esposito et al. (2008). As the number of statistically significant features has grown, it has become useful to classify them for the purposes of cataloging. We define three classes: Moonlet, Icicle, and Core, which visually classify the shapes of features seen to date in the occultation profiles of Saturn’s F ring. Two features fall into the Moonlet class. Each is opaque in its occultation, which makes them candidates for solid objects. A majority of features are classified as Icicles, which partially block stellar signal for 22 m to just over 3.7 km along the radial expanse of the occultation. The density enhancements responsible for such signal attenuations are likely due to transient clumping of material, evidence that aggregations of material are ubiquitous in the F ring. Finally, the variety of core region shapes displays how even the general shape of the F ring is ever-changing. The core region of the F ring (typically ~10 km wide) usually has a smooth U-shape to it, but the core region takes
the shape of Ws and Vs in some occultation profiles. Our lengthy observing campaign reveals that icicles are likely transient clumps, moonlets are possible solid objects, and cores show the variety of F ring morphology. We suggest that icicles may evolve into moonlets, which are an order of magnitude less abundant.

**Key Words:**

Occultations
Planetary rings
Saturn, Rings
Ultraviolet observations
1.

**Introduction**

Since its discovery (Gehrels et al., 1980), the F ring of Saturn has been the focus of many observations and revealed new insights into ring dynamics and evolution. Cuzzi and Burns (1988) interpreted Pioneer 11 depletions in magnetospheric particles in the region, which they attribute to small moonlets (<10km). Later, Voyager observations revealed broad strands and burst events that showed the F ring as variable on short time scales and over azimuthal distances (e.g. Lane et al., 1982; Smith et al., 1982; Murray, 1992; Murray et al., 1997; Showalter, 2004). Kolvoord et al. (1990) found periodic brightness enhancements in Voyager images of the F ring that are consistent with Prometheus apoapse passages. During the 1995 ring plane crossing, edge-on observations identified small bodies (Bosh and Rivkin, 1996; Nicholson et al., 1996). These observations show the F ring is a mix of large and small particles with significant spatial and temporal variability. This large-scale variability is apparent in imaging of both the F ring core including kinks, knots, braids, and clumps (Smith et al. 1981, 1982; Showalter 1998; Poulet
et al. 2000; Murray et al. 2005, 2008) and the F ring strands in the form of a kinematic spiral (Charnoz et al., 2005).

Since the Cassini spacecraft reached Saturn, the F ring has been a target for study of small body formation and ring evolution. Esposito et al. (2008) report 1-10 km bodies, double core regions, and temporal variability from UVIS stellar occultation observations. VIMS (e.g. Hedman et al., 2007) co-observed at least one of these features. ISS images show kinks, knots, braids, strands, clumps, and spirals in the F ring (Charnoz et al. 2005; Murray et al. 2005, 2008; Showalter 2004; Poulet et al. 2000). Murray et al. (2008) observe structures created by Prometheus in ISS images. Beurle et al. (2010) show that Prometheus makes it possible for “distended, yet long-lived, gravitationally coherent clumps” to form. Esposito et al. (2011) find evidence that clumping is correlated to the location of Prometheus, indicating that accretion of small bodies in the F ring may be triggered by the moon’s influence.

Models have attempted to explain the distribution of small bodies in the F ring as the equilibrium between accretion and fragmentation. Barbara and Esposito (2002) (hereafter BE02)
predict that the F ring evolves to a bimodal distribution of bodies that has a large population of dust as well as few km-sized bodies. In addition, numerical and semi-analytical works have predicted clumping in narrow rings (Longaretti, 1989) and rings in a planet’s Roche zone (Ohtsuki, 1993; Salo, 1995; Karjalainen and Salo, 2004). N-body simulations of the A and B rings show short-lived clumping of material that could also occur in the F ring (Lewis and Stewart, 2009). Thus, the F ring is an interesting place of exploration as a testing ground to compare to clumping processes elsewhere in the rings (e.g., A ring propeller belt or B ring edge). Additionally, UVIS affords us the opportunity to detect aggregates tens of meters to a few kilometers in size. UVIS has much better spatial resolution than the cameras, which have achieved 500m/pixel thus far in the F ring (Porco et al., 2005, Murray et al., 2008), so we can probe deeper to understand the processes occurring at scales as small as tens of meters.

2. **F ring observations**
The Cassini Ultraviolet Imaging Spectrograph (UVIS) has a High Speed Photometer (HSP) channel designed to observe stellar occultations (Esposito et al., 1998, 2004, 2005). The effective wavelength for this channel is about 1500 Å. As of September 22, 2010, UVIS has observed 101 stellar occultations by the F ring. We identify individual occultations in this manuscript by the occulted star and the “rev” number during which the F ring occulted it, where “rev” refers to a Cassini orbit (apoapse to apoapse), which are numbered sequentially (0,A,B,C,3,4,5…). These data are available on the PDS, arranged by instrument, year, and day of year. Occultation data file names start with HSP.

The geometry of each occultation is calculated based on the positions of the star and the position of the spacecraft derived from the appropriate SPICE kernels. The individual reconstructed Cassini spacecraft trajectory SPICE kernels that have coverage of the occultations were used (all reconstructed kernels except for ‘090415BP_SCPSE_09105_09115.bsp’, ‘101222BP_SCPSE_10353_11015.bsp’, and ‘101229AP_SCPSE_10363_11015.bsp’). These are available via anonymous ftp.
atftp://naif.jpl.nasa.gov/pub/naif/CASSINI/kernels/spk. This information was used to predict the position (radius and inertial longitude) of the star in Saturn’s ring plane as a function of time, listed as radial position and longitudes in Table 1. The Saturn pole direction used was from ‘cpck17Dec2010.tpc’.

These observations allow us to measure the F ring’s opacity at various times, longitudes, and angles (Colwell et al., 2006, 2007, 2010), from which we identify individual structures throughout the ring. In addition to observing long-lived features consistent with “strands” (Albers et al. 2009, 2012), we also identify smaller, non-repeatable structures in isolated occultation profiles. With occultations, follow-up observations are extremely difficult if not impossible, so we use optical depth of such small features as an estimator of longevity as did Esposito et al. (2008). The higher a feature’s optical depth, the longer it takes to diffuse apart, so it will be a longer-lived (meaning surviving multiple orbits) object (Shu and Stewart, 1985).

3.
Search Method

The method used to identify significant attenuations in the stellar signal during occultations is adapted from the search method described in Esposito et al. (2008). The search method consists of two parts: a test for statistical significance and a subsequent persistence test. We have improved the method presented by Esposito et al. (2008) by searching over a uniform radial range of distance from Saturn, probing different bin sizes, and requiring features to be of greater statistical significance than they did.

First, we considered a feature that was independently verified by VIMS. The feature, nicknamed “Pywacket,” was simultaneously observed by VIMS and UVIS during the occultation of α Sco rev 13 (Esposito et al. 2008). Both instruments observed a significant increase in opacity ~600 m in radial width. Since this detection is in both UV (~1500 Å) and near IR (2.92 μm), it assures this event was not a statistical fluctuation but a real event. Figure 1 shows the two observations. We used this confirmed detection to refine our search algorithm for similar features in the UVIS data.
The search algorithm has two completely automated parts. The first searches for statistically significant attenuations in the stellar signal, while the second requires a feature to have a minimum optical depth.

1) For each occultation, the data in the radial range 139,000 km to 141,000 km are binned at a given radial size. The number of integrations per bin varies among occultations as the geometry and thus resolution varies; therefore, we choose a fixed radial bin size and sample over a fixed radial range in order to make this test more consistent than Esposito et al. (2008). Then, we offset the start of binning, creating N different occultation profiles for a bin size of N time integrations for every possible distinct binning of the data. Next, we determine a smoothed baseline value for the F ring opacity. To do so we take a running mean from approximately 5 km of stellar signal, or number of photons detected, surrounding and including each bin. This definition for the baseline was compared to alternatives, including medians, polynomial fits, splines, and various other radial ranges for the running mean; however, we select this method
because the Pywacket feature is most statistically significant using this particular baseline (specifically, a running mean of 81 bins of 5 integrations surrounding and including the center bin).

Assuming the HSP signal is described by a Poisson distribution, well-satisfied for our data and confirmed by observations of blank regions, where $\mu$ corresponds to the baseline value and $C$ is the binned stellar signal at a particular bin, the probability of measuring a value of exactly $C$ is given by

$$P(\mu, C) = \frac{e^{-\mu} \mu^C}{C!} \quad (1)$$

To find the probability that the stellar signal would be less that or equal to $C$ at that bin, we sum the distribution over all signal values less than $C$:

$$P(\mu, \leq C) = \sum_{j=0}^{C} \frac{e^{-\mu} \mu^j}{j!} \quad (2)$$

We perform this calculation for each bin, $i$, in the data set to find $P_i = P(\mu_i, \leq C_i)$. We then multiply $P_i$ by the number of tested bins in the data set, $\nu$. This gives $m = \nu \cdot P_i$ (Colwell et al., 2013).
1990). Events with $m < m_{\text{significant}}$ are statistically significant because it is unlikely that such an event would occur by chance in the profile. Mathematically, the critical $m$ value $m_{\text{significant}}$ is 1 and used for most occultations; however, for a handful of observations of bright stars when raw stellar signal exceeds 128 counts the value is set at a more conservative 0.1. This is due to compression of the UVIS data (square root nine compression, see Esposito et al. 2004) that reduces the transmitted data to 8 bits, which can produce spuriously low counts. The value $m_{\text{significant}} = 0.1$ was estimated from testing a number of surrogate Poisson processes after compression was applied. This is a new requirement beyond that reported in Esposito et al. (2008).

If a feature is flagged in at least one of $N$ different starting point binnings, we count in exactly how many different binnings it is flagged. This number $K$ is then compared to $|N-W|$, the difference in bin size $N$ and feature size $W$, where $W$ is full width at half maximum (FWHM) in unbinned data. For a feature of width $W$, just barely detected by our method, $|N-W|$ is the expected number of arbitrary starting points where it passes the statistical test (for $W \leq 2N$). For
a feature to be significant, \( K \) (the number of configurations in which the feature was flagged) must be greater than \(|N-W|\). This procedure is repeated for six different radial bin sizes: 25 m, 100 m, 250 m, 500 m, 1 km, and 2 km. We impose a more rigorous requirement than Esposito et al. (2008); only if a feature is significant in at least two different bin sizes will it be reported and flagged for the next test, the “persistence” test.

2) In the “persistence” test, each flagged event is examined to determine its width and peak opacity at the radial bin size in which it was significant. To be included in our list, the maximum binned normal optical depth (\( \tau = \tau_{\text{observed}} \sin B \)) of the feature must be at least as large as Pywacket (\( \tau_{\text{max}} = 0.4 \) when binned to 500 m). It should be noted that since we use a statistical test, it is possible that some spurious events are recorded and that some real features are missed. The largest uncertainty of this test is the unknown F ring background model (without features) with which to compare our possible features.

The radial width is the full width at half maximum of the consecutive integration periods that are part of the feature in an unbinned profile. Peak normal optical depth is the maximum
value for the feature from the binned data. Because of the optical depth requirement, $\tau_{\text{max}} > 0.4$, the ring particles in such aggregations collide multiple times each orbit (Shu and Stewart, 1985). The collision rate is proportional to the observed optical depth $\tau$, and the number of collisions for a particle to escape the clump is proportional to $\tau^2$. The clump lifetime is estimated by the ratio of the number of collision required for particle escape to the collision rate, $\tau^2/\tau$, thus it scales as the clump optical depth. An aggregate will diffuse apart as it suffers more collisions and eventually will break apart entirely. This means that more opaque structures will persist for multiple orbits.

Our search method introduces two qualifications to the characteristics of found features. First, star brightness varies from occultation to occultation. The Poisson statistics of a weak star are noisier than those of a bright star. Because peak normal optical depth is a feature-selection criterion, the brightness of a star may have some effect on selection; however, the persistence test requires a minimum optical depth that is derived from a confirmed feature (obviously not a statistical fluctuation), so we probably do not exclude any real features based purely on low
statistical significance from dimmer stars. Another characteristic of our search method is a bias toward azimuthally elongated features in the F ring. An occultation that slices through the F ring has a higher probability of the occultation path intersecting a clump if the clump is elongated in azimuth. It follows from this bias that the features detected in this study may be elongated in longitude. Simulations of ring material (Lewis and Stewart, 2009) and observed propeller structures (Tiscareno et al., 2008) have shown how ring material shears out over azimuth, thus elongating clumps. UVIS HSP occultations cut the ring almost radially as the radial speed is typically a few km/s, but ring material orbits beneath the occultation track at ~17 km/s, thus the occultation cuts are typically very slanted in the corotating frame providing some azimuthal component to the observed ring structure. We account for the elongation and corotation biases in the size distribution of features reported later in this paper (Section 5). We report only the apparent radial width of features here, but such features likely are not spherical and may have different widths in other dimensions.
4. Data Analysis

We apply this search algorithm to all 101 occultation profiles of the F ring. This yields 27 events, distributed in radial width from 22m to 3.7 km (see Table 1). We performed the same search for each of the 101 occultations in the region 138,000 ± 1,000 km, where we expect unocculted stellar signal. As expected, we found no features that pass our search criteria in this region; therefore, we conclude the features we find in the F ring region almost certainly represent real structures in the F ring.

Seven of the 13 features (Events 3, 6, and 9-13) reported in Esposito et al. (2008) were not found by this new search method. All seven are excluded because they do not pass our stricter statistical test; the set bin size of the Esposito et al. (2008) search algorithm was coincidently optimized for these features, but because they are not statistically significant at different bin sizes they do not pass our more conservative test. The six features from Esposito et al. (2008) that
pass the new stricter test are reported as Events 1 through 6 in Table 1 in this manuscript. We find the 21 other features in occultations not searched in Esposito et al. (2008).

4.1 Classification

With 27 features detected over the course of 101 observed occultations by the F ring (Table 1, Figure 2), the authors have found it useful to develop a classification scheme. Three categories are apparent: Moonlet, Icicle, and Core (Table 2). These names describe the shape of the feature as seen in signal attenuation in the occultation profile. As such, the names are not intended to exactly identify the physical object obstructing stellar signal, as different types of objects may be associated with one type of observed occultation feature (and vice versa) because they are indistinguishable in the one-dimensional occultation profile. Each class has defining characteristics that distinguish it from the others. Two of the classes, Cores and Icicles, are broken down into sub-classes due to variations in the morphology of constituent members. The
number of features in each class is listed in Table 2. This system of classification seeks to order the types of features within the F ring.

4.1.1 Moonlets

These features are quite distinct from any other features yet observed. Members of this class attenuate stellar signal to background levels, so we interpret them as opaque features. This indicates that the objects causing these observed opaque features may be solid objects, rather than completely loose aggregations of material that are capable of letting light pass through their porous interiors. Unlike an atmosphereless-moon occultation with vertical drop-offs in signal, the edges of these features exhibit a steep but sloped decrease in signal, indicative of a thin, loosely-aggregated surface layer around a solid object. Thus far, two Moonlets have been
observed. One of the features, nicknamed ‘Mittens,’ observed during the occultation of $\alpha$ Leo during rev 9, blocks all stellar signal for a radial distance of 594 m, with small transition regions of attenuation in signal on both sides (Fig. 3a). The other feature in this class, nicknamed ‘Sylvester,’ is observed in the occultation of $\alpha$ Ara, Ingress, rev 90. This feature is interesting because it is the only one that lies in the core-like inner strand of the F ring (Albers et al. 2012), while all of the other 26 observed significant features lie in or near the core of the F ring. Although smaller in width (107 m) than the other Moonlet, Sylvester also exhibits steep drop-offs in stellar signal to the background level (Fig. 3b).

[Figure 3a embedded here]

[Figure 3b embedded here]

4.1.2

Icicles

The Icicle class of F ring features has the largest number of members at 15. This class is so named because the abrupt drop in stellar signal resembles an icicle hanging from eaves.
Members of this group are smaller formations, usually under a kilometer in radial width (Fig. 4), and can be divided into two subclasses. The Icicle nicknamed Pywacket in Esposito et al. (2008) is an example of a simple Icicle, or one that is alone in a region. The other subclass of Icicles is the multi-icicle, which occurs when several simple-icicles cluster in a confined region. An example of this can be seen in \( \alpha \) Ara rev 63 (Fig. 4c), with the inner, wider feature being a multi-icicle and the outer, smaller feature a simple-icicle. Eight multi-icicle significant features are too many to be created by randomly located independent events and demonstrate the tendency of multiple features to occur together.

[Figure 4 embedded here]

4.1.3

Cores

Another class of observed features is Cores. The F ring typically has one central core region that is “U”-shaped and approximately 10 km wide. We identify two other variations in
core region shape: “V” and “W”. These designations describe the signal attenuation along the radial direction of the ring in an occultation profile. The “V”-shaped core is likely a concentration of material in a dense, ~500 m-wide stream surrounded by a linear decrease in optical depth on both sides, as pictured in the α Ara, rev 96 egress occultation profile in Fig. 5e. Of the ten features included in the “cores” class there are two significant “V”-cores seen (other “V”-shaped cores appear within the scope of this study, but those are not included in our list because they do not qualify as statistically-significant features). Another common F ring core shape is the “W.” A possible explanation for the “W”-shaped core could be that described by Brophy et al. (1990). They discuss such a configuration due to particle-size segregation, leading to an inner region of low optical depth flanked by roughly equal-sized regions of higher opacity, like the ε Cen, rev 65 occultation profile in Fig. 5b (nicknamed Fang 1, 2). We identify a total of eight significant “W”-core features over the specified observing campaign.

[Figure 5 embedded here]
5.

Discussion

Table 1 lists our features, showing the broad range of size, shape, and optical depth of the significant features we observe in the F ring. The table gives the location of each feature with respect to the F ring core, the location of which is defined by the visually-determined point of greatest attenuation. Features are seen inside, outside, and at the F ring core location. From our sample of significant features, there is only one major outlier from the ring core, the Moonlet nicknamed Sylvester, which is also the only feature found in the core-like inner strand (Albers et al., 2011) region. The classification of this large number of F ring events by morphology reveals the prevalence of certain shapes, sizes, and opacities. Although these classes are based on the shape of the signal attenuation in the occultation profile, we may associate them with different types of objects embedded in the ring. Cassini UVIS occultations have certainly revealed that the F ring core takes many different shapes and is not azimuthally symmetric. Certain longitudes experience a narrowing of the core resulting in a “V”-shaped core (Esposito et al., 2008).
Meanwhile, particle size segregation may result in the “W”-shaped cores in other regions (Brophy, et al., 1990; Lewis and Stewart, 2009). Icicles are density enhancements that we conclude indicate elongated clumps of ring particles (Lewis and Stewart, 2009). It is important to remember here that each occultation feature classification does not necessarily correspond to one type of object in the ring. For example, the multi-icicle “Whiskers” is also consistent with moonlet wakes (Albers et al., 2012). We interpret the Icicles as temporary aggregates that we call “clumps” and the Moonlets as possible solid bodies.

The two Moonlet-class features lead us to assess the type of object responsible for such signal attenuations. As the name suggests, these objects may be solid objects embedded in the F ring; however, their edges in occultations are not perfectly sharp (as obtained in moon occultations, e.g. Hansen et al. 2006) but have a gradient. Works of Porco et al. (2007) and Charnoz et al. (2007) have established that solid bodies within rings accrete the material until their Roche lobe is filled. Further mass increase requires some additional physical process, such as compaction. Thus, at any point the moonlets within the F ring have roughly filled their Roche
lobes, and, while their gravity still attracts the ring particles, they are not bound to the moonlet. The attracted particles probably form a “skirt” of loose material around the moonlets. In order to model this we envision the moonlet as a triaxial solid body with axes (a in azimuthal, b in radial, and c in vertical dimensions) and a “skirt” of loose material of width h. The attenuation of star light by loose material is modeled as a linear decrease of transparency $t = \exp\left(-\frac{\tau}{|\sin(B)|}\right)$ from opaque solid core to the ring background. In this equation, $\tau$ is optical depth and $B$ is the elevation angle of the occultation, which is $9^\circ$ for the $\alpha$ Leo, rev 9 occultation with Mittens and $-54^\circ$ for $\alpha$ Ara, Ingress, rev 90 with Sylvester. We then simulate an occultation cut across the center of the Moonlet in the moonlet corotating frame. In both cases of Mittens and Silvester the geometry is such that the moonlet is seen from the side, making fits sensitive only to the azimuthal extent of the moonlet (a,h). The radial axis b and vertical axis c are unconstrained. The azimuthal size of the body (a) gives the largest contribution to the width of the opaque part. While the width itself is wellconstrained from the data, the contribution from radial (b) and vertical (c) axes are not zero, thus giving significant uncertainty for a. Thus, we deem that a
chi-squared minimization is not warranted, and instead we presented a possible solution for $a$ and $h$ that was found by visually inspecting plots with varying values for $a$ and $h$ in increments of about 5%. A typical successful fit to UVIS data is shown in Fig. 3a,b. Test fits with different aspect ratios yield nearly the same body azimuthal axis of about $a=500m$ (120m), and loose material of width $h=200m$ (150m) for Mittens (Silvester). Comparing the various plots we can estimate that the uncertainty in $a$ and $h$ is at least 20%. In addition, UVIS and VIMS observed features coincidently on two different occasions: simple-icicle Pywacket in $\alpha$ Sco rev 13 egress and multi-icicle “Felix” in $\alpha$ Sco rev 29. We infer that the objects responsible for the signal attenuation in these observations are elongated in the azimuth. $\alpha$ Sco is a double star whose member stars can individually be observed in IR and UV, respectively. Thus, an angular separation of the two observations during the rev 13 occultation means that Pywacket was actually observed at two different inertial longitudes, first by UVIS and then after 1.18s by VIMS, which is why the two observations are at different distances from the core in Fig. 1. Taking into account the projected speed of the occultation track and the orbital motion of the
body between two observations we obtain the actual azimuthal separation of about 1.2 km, as compared to the 763 m radial width of the feature. This is further evidence that such clumps of material are azimuthally elongated.

We compare these opaque features to models of moonlet belts in Saturn’s rings. Cuzzi and Burns (1988) predict a moonlet belt surrounding the F ring, but none of the opaque features occurred outside of the immediate region surrounding the core or secondary-core region. BE02 predict a bimodal size distribution of moonlets in the F ring, but the observed number (2) is inconsistent with the number of such objects predicted from their models (cf. Fig. 6). From the one measurement of the 594 m feature, classified as Moonlet Mittens, in one of 101 independent occultation profiles, we estimate $1.5 \times 10^4$ Mittens-sized bodies in the F ring. From Esposito, et al. (2008), we have for spherical objects

$$N_{Fring} = \frac{n_{obs}}{n_{acc}} \frac{2\pi R}{W_{obs}}$$

and from that we find the total mass of such objects in the F ring to be
\[ M_{\text{total clumps}} = \sum_{W_{\text{obs}}} \frac{\pi}{6} \rho_{\text{clump}} W_{\text{obs}}^3 N_{\text{Fring}} \]  

where \( n_{\text{obs}} \) is the number of observed features (\( n_{\text{obs}} = 1 \) for each individual feature), \( n_{\text{occ}} \) is the number of occultation profiles (\( n_{\text{occ}} = 101 \)), \( W_{\text{obs}} \) is the observed FWHM feature width, \( R \) is the Saturnocentric distance of the F ring (\( R = 140221.3 \) km), and \( \rho_{\text{clump}} = 0.235 \) g cm\(^{-3}\) is half the density of Prometheus. Likewise, \( 8.2 \times 10^4 \) Sylvester-sized objects may exist in the ring, as compared to \( \sim 100 \) such features in the BE02 model. We estimate the total mass of Moonlets and Icicles derived from observations using Eqs. 3 and 4 to be \( 6.1 \times 10^{15} \) kg. Such additional mass would accelerate (e.g. Null et al., 1980) the precession rate of Prometheus by \( 2.76 \times 10^{-5} \) degrees per day, which would have been observable (French et al., 2003, 2006). Furthermore, that mass equates to a surface density of \( 800 \) g cm\(^{-2}\), a 20-fold increase over the A ring. As we do not observe such a precession or surface density, we reexamine our calculation. One thing to notice is that the few largest features in the distribution contribute the most mass to the total. Table 1 lists the mass contribution from each size of object. The largest feature, number 25 Felix,
accounts for 56.1% of the total extrapolated mass of spherical clumps in the F ring. The observation of a single large Icicle may not represent the entire population of similarly-sized features in the F ring, which contributes to an overestimate of the total mass of clumps in the ring. This large mass estimate supports that the features are likely not spherical, rather they are elongated clumps more like triaxial ellipsoids, as suggested by the occultation geometries earlier in the manuscript. The features are probably flattened and have a radial width about one tenth that of the azimuthal length, an axial ratio typical of gravitational wakes and propeller structures in the A ring (Colwell et al., 2007; Lewis and Stewart, 2009; Salo and Schmidt, 2010; Tiscareno, et al., 2010).

For elongated objects, \( W_{\text{obs}} \) may significantly underestimate the length of the feature, leading to an overestimate of \( N_{\text{Fring}} \). Since the orientation of the occultation cuts is not random in the ring plane, and aggregations are likely more azimuthally elongated than radial, \( N_{\text{Fring}} \) must be considered an upper limit. We generalize Eq. 5 as an upper limit of the number of bodies of a certain size in the F ring, accounting for a triaxial ellipsoid by including a factor \( \rho_{\text{axes}} = a/b = b/c \) to
account for the ratio of the azimuthal length of the body to the radial width and radial width to vertical thickness.

\[ N_{\text{fring}} \leq \frac{n_{\text{obs}}}{n_{\text{occ}}} \frac{2\pi R}{\rho_{\text{axes}} W_{\text{obs}}} \]  \hspace{1cm} (5)

\[ M_{\text{total clumps}} = \sum_{w_{\text{obs}}} \frac{\pi}{6} \rho_{\text{clump}} W_{\text{obs}}^3 N_{\text{fring}} \]  \hspace{1cm} (6)

Equation 5 reduces to Eq.3 for a sphere (\(\rho_{\text{axes}}=1\)). Figure 6 includes this upper limit for \(\rho_{\text{axes}}=10\). Assuming \(\rho_{\text{axes}}=10\), we can now extrapolate the total mass of vertically-flattened, ellipsoidal clumps in the F ring from this number. Using Eq. 6, we find a total mass of 6.1 x 10^{14} kg, equivalent to a moon of Prometheus’s density with radius of 6.8 km. Assuming the radial width of the F ring is ~6 km, this mass equates to a surface density of 11.7g cm^{-2}, and would cause a change in Prometheus’ precession rate of 2.76x10^{-6} degrees per day, which is below the detection threshold. Since the features we see are likely elongated, this resolves the mass problem we found previously for spherical clumps because there are fewer elongated clumps although each is as massive.
We report the cumulative size distribution of the number of features in the F ring, calculated using Eq. 5 and the 9 features reported as Moonlets and Simple Icicles. We consider only the Moonlets and Simple Icicles because those are the feature classes that are identified with individual triaxial clumps, whereas the core class is instead identified with core-shape dynamics and the multi-icicles are likely composed of multiple simple icicles. This observed cumulative size distribution is compared to simulations of aggregation and disaggregation in the F ring by BE02 in fig. 6. BE02 simulated the evolution of the F ring including tidally-modified accretion. This led to a predicted bimodal differential distribution of bodies in the F ring, with a peak in the size at a few kilometers. It is obvious that we do not observe the bimodal distribution predicted by BE02, but rather a continuous power law \( n \propto r^{-Q} \) that is best fit by cumulative power law index \( Q = 1.5 \), which is equivalent to a differential power law index of \( q = Q + 1 = 2.5 \) (see the next paragraph for another method of \( Q \)-value determination). In variables we defined in this paper, \( N_{\text{Fring}}(>w_{\text{obs}}/2) (w_{\text{obs}}/2)^{-Q} \). At sizes under one kilometer, the BE02 prediction of the number of bodies is much larger than the observed distribution; however, for an azimuthal axis
toroidal axis ratio of 10, we only have a 0.57 chance of observing a feature in 101 occultations that would match BE02’s larger size mode (width = 1-10 km), so we cannot yet compare our observations to the BE02 distribution at sizes above a kilometer. The two distributions may be different for several reasons. First, BE02 simulate the equilibrium distribution of a model of solid, spherical moonlets in the F ring, but not loose-packed, probably-elongated aggregates of material as is indicated by Cassini observations. Also, BE02 include only tidally-modified accretion. If other processes like melting, sticking, sorting, or compaction are important, this would most likely modify the predicted distribution. Additionally, BE02 assumed a sharp threshold for accretion. If the ratio of colliding bodies’ masses is large enough they fragment 100%, otherwise they accrete 100%. In Fig 6, one can see the BE02 model (solid curve) does not match the observed cumulative size distribution of our features. In fact, for the lower end of the size rangesampled, BE02 predictions are significantly larger than the number UVIS detects.

[Figure 6 embedded here]
We use another method to obtain the most likely differential slope q of the distribution. We first examine the raw data presented in Table 1, and then we correct the (size-dependent) correction factor due to observational biases (see below) present in Eq. 3 and Eq. 5. The small number of data points presents the major challenge, and we use a simple surrogate model of power-law random numbers with the differential slope $q_{\text{raw}}$ and sizes between $[s_1,s_2]$ to match the data. Drawing random numbers to represent the observed distribution mimics what UVIS does; that is to say, randomly observe occultation cuts through the F ring at random longitudes and times. Numerical experiments indicate that distributions with slope $q_{\text{raw}} > 2$ are ruled out for two reasons. First, the distribution does not meet the data points at smaller sizes, while in the numerical experiments it is exactly the more numerous smaller sizes that are the most indicative of the underlying distribution as seen in Fig. 7. Second, the drawn random numbers cluster at the smallest sizes, while if we look at Table 1 we see that sizes are almost equally distributed between smallest and largest. In Fig. 7, one can see that by far the better fit is obtained with distributions with $1 < q_{\text{raw}} < 1.5$. This conclusion stands in both cases if we consider all data.
(including multi-icicles) or only the sub-selection of moonlets and simple icicles. The shallow distributions with $q_{\text{raw}}<1.5$ are also sensitive to the upper size cut-off $s_2$ (contrary to $q_{\text{raw}}>2$).

While it is tempting to conclude that there is indeed an upper cut-off, or at least a knee between 1 and 10km, it is best to refrain due to the scarcity of the data. The last step is to consider the bias in the detected sizes. UVIS occultations are only one-dimensional cuts across the F ring and provided that the features scale roughly the same in all three dimensions, the smallest features are hardest to detect, since the potential target is proportional to the feature size. Thus the simplest model is to consider a factor of $1/s$ that links the real F ring distribution and the actually observed UVIS data (as in Eq. 3 and Eq. 5). In other words, even if there was the same number of 100m and 1km objects in the F ring, UVIS experiment is 10 times more likely to detect 1km objects. Therefore, we conclude that the true differential slope of the size distribution of F ring features is $2<q<2.5$, which is consistent with the simple power-law fit to the cumulative distribution in Fig. 6.

[Figure 7 embedded here]
The sample of significant features in the Icicles and Moonlets classes sheds some light on the evolution of clumps. The largest class by far is that of Icicles. It is natural to imagine Moonlets as a possible future stage of the Icicle. Optical depth indicates clumping because more densely aggregated material blocks more light. Thus, if looser clumps of material (Icicles) compact into denser, less porous aggregates they may be observed as an opaque Moonlet in an occultation. Since the Moonlet class is the smallest class with only two observed members, it seems that this compaction state is rare. We note that when Icicle and Moonlet optical depths are compared to the relative position of Prometheus optical depths are largest for features located near the antipode of Prometheus’s orbit (separated from Prometheus in longitude by 180°) (Esposito et al., 2011). This rarity of opaque Moonlets compared to clumps is consistent with Esposito’s proposal that Prometheus triggers a cycle of aggregation and disaggregation that only infrequently results in formation of a coherent object.
Conclusion

Stellar occultations show features in Saturn’s F ring that indicate azimuthally-elongated clumping of ring material. Classification of such significant features demonstrates that while clumping may be a common process, consolidation into an opaque object, like a Moonlet, is not.

Acknowledgments

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TABLE CAPTIONS

Table 1.
Characteristics of each significant feature found in 101 UVIS F ring occultation profiles. The occultations are named with the rev number during which an observation was made and include “I” or “E” to denote “ingress” or “egress,” respectively, for observations that included both segments. Icicles and Moonlets are nicknamed because they are likely associated with specific objects in the ring, while Cores are not because they are varying shapes of the ring. Longitudes and reference radii were computed using the eccentric, inclined F ring model of Albers et al. (2011). “Distance to core” is the radial position of the feature relative to the observed F ring core reference radius, which is determined by visually selecting the position of greatest attenuation. The F ring “core” is the region of greatest attenuation in an occultation, coincident with the highest density region of the ring. Note that the two opaque features, 1 Mittens and 19
Sylvester, are listed with a finite optical depth because those values are the maximum optical depth values for those particular occultations.

Features noted with an “*” (Events 1-6) are also reported in Esposito et al. (2008) as Events 1, 2, 4, 5, 7, and 8; however, the other seven features reported in Esposito et al. (2008) did not pass the stricter test presented here. No new features were found in previously searched occultations.

The geometric values given here are calculated using the individual reconstructed Cassini spacecraft trajectory SPICE kernels that have coverage of the occultations used. These are available via anonymous ftp at ftp://naif.jpl.nasa.gov/pub/naif.CASSINI/kernels/spk/ . For the geometry in this study, ‘cpck17Dec2010.tpc’ was used.

**Table 2.**
This table lists the number of significant features in each class.

**Table 1.**

47
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<td>10</td>
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Table 2.
FIGURE CAPTIONS

Figure 1. VIMS (solid, smooth curve) and UVIS (thinner curve) $\alpha$Sco egress, rev 13 occultation data overplotted. The UVIS curve is scaled to match the VIMS unocculted stellar flux (outside the plotted range). The two instruments have different spatial resolutions, but both clearly detect Pywacket outside the F ring core. UVIS identifies the clump at $\sim$8 km, VIMS at $\sim$10 km because the instruments sample different inertial longitudes of the ring; while separately observing each of the stars comprising the double star $\alpha$Sco. This situation allows for the observation of an offset that is indicative of an elongated clump.

Figure 2. All 27 of the occultations where significant features were observed. Each is labeled with the type of feature observed and the star name and rev number of the occultation. The occultations are named with the rev number during which an observation was made and include “I” or “E” to denote “ingress” or “egress,” respectively, for observations that included both segments. Each feature is labeled with an arrow and the event number from Table 1. All plots are over the same radial range, which is why $\alpha$Ara, rev 90, Ingress is labeled “Not in range”
because the Moonlet appears in the core-like inner strand region (Fig. 3b). Longitudes and reference radii were computed using the eccentric, inclined F ring model of Albers et al. (2011). “Distance to core” is the radial position of the feature relative to the observed F ring core reference radius, which is defined by the visually-determined point of greatest attenuation. The F ring “core” is the region of greatest attenuation in an occultation, coincident with the highest density region of the ring. All occultations have signal binned to 100 m.

**Figure 3.** The two features classified as Moonlets because both have sharp edges and attenuate stellar signal to the background level. Our simple model demonstrates that a realistic triaxial ellipsoidal body with a semi-transparent surface layer matches the data from the two occultations in this figure. Since in both geometries the body is essentially viewed from the side ($B(\alpha$ Leo, rev 9) = 9° and $B(\alpha$ Ara, Ingress, rev 90) =−54°), the radial and vertical dimensions are unconstrained. The thickness $h$ directly gives the transition from the background to the ring level, which does not warrant a sophisticated model and we simply employed a linear function.
a) Occultation profile of $\alpha$ Leo rev. 9 in raw counts. The feature at 139917 km is “Mittens.” Fits of the occultation constrain the azimuthal body axis $b$ to be 500m and unconsolidated layer width $h=200$m.

b) Occultation of $\alpha$ Ara rev 90 in raw counts. The Moonlet nicknamed “Sylvester” is at 139930 km. The dimensions $b=120$m and $h=150$m are constrained by the fits for this occultation.

**Figure 4.** Members of the Icicles class. Features are labeled with an arrow and their “Event number” from Table 1. Occultations are identified by the star occulted and the rev number during which the observation occurred.

**Figure 5.** Statistically-significant core regions. a. Occultation of $\alpha$ Ara rev 34 egress. We classify this feature, nicknamed Butterball, as a W-core. b. Occultation of $\epsilon$Cen rev 65. Example of W-core, nicknamed Fang 1 and Fang 2. c. Occultation of $\alpha$ Ara 79 shows W-core structure. d. Occultation profile of $\alpha$ Ara 90 egress. We classify this as W-core structure. e. Occultation profile of $\alpha$ Ara 96 egress. This is a V-core. f. Occultation profile of $\epsilon$ Cas 104 egress shows
another W-core. g. Occultation profile of $\alpha$Vir 124 shows another W-core. h. Occultation profile of $\alpha$Vir 134 shows another V-core.

**Figure 6.** Cumulative size distribution of significant features in the Moonlet and Simple Icicle classes extrapolated from UVIS observations reported in this paper (black diamonds) and predicted by BE02 (solid line). We do not include the core class of features in this distribution because they are not comparable to the objects described by BE02. We also exclude the multi-icicles from this analysis because we describe them as accumulations of simple icicles rather than one triaxial object. The black diamonds plotted are calculated upper limits on the number of ellipsoidal clumps in the F ring (eq. 5 for $\rho_{\text{axes}}=10$), accounting for observational biases due to clump elongation. The observed distribution, with a fitted cumulative power law index of $Q=1.5$ (overplotted in red) does not match the bimodal distribution predicted by BE02 for sizes smaller than a kilometer; however, for $\rho_{\text{axes}}=10$, we only have a 0.57 chance of observing a feature in 101 occultations that would match BE02’s larger size mode, so we cannot yet compare our observations to the BE02 distribution at larger sizes.
**Figure 7.** Comparison of observed and surrogate cumulative size distributions. Black is used for UVIS data, which includes only moonlets and simple icicles, and blue for all UVIS data (excluding Cores), while red represents the surrogate random number distribution. UVIS data points are the raw data from Table 1, without correcting for the 1/s bias (Eq. 3). Since the cumulative distribution is insensitive to the possible binning (by the definition) we choose the bins to correspond to actual data points (UVIS or surrogate). We display three different random number realizations (from top to bottom: seeds are -7, -8, -9), each normalized to 1 and offset for ease of viewing.

a) Top panel shows surrogate random number distributions for $q_{\text{raw}} = 2$

b) Bottom panel shows surrogate random number distributions for $q_{\text{raw}} = 1.2$.

**FIGURES**

*Figure 1.*
Figure 2.
Figure 3a.
Figure 3b.
Figure 4.
Figure 5.
Figure 6.
Figure 7a.
Figure 7b.
Model (red):
q = 1.20000
s1 = 0.0300000
s2 = 1.500000

Cumulative distribution

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Normalized stellar signal vs Distance from core (km)

Not visible in this range
We find 27 statistically significant features in Saturn’s F ring.

Features are divided into three morphological classes.

Icicle- and Moonlet-class features correspond to aggregates elongated in azimuth.

We conclude that consolidation to an opaque object is rare compared to clumping.