Evolution of Irregular Satellite Swarms

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Aim

i. Develop a simple (but not too simple) model of irregular satellite collisional evolution

ii. Apply it to:

   Solar System (validation)
   Fomalhaut b
   Swarms around extrasolar planets
Properties of Irregulars
Jewitt & Haghighipour 2007
Bottke et al. 2010

Cumulative Number vs. Diameter (km) for Jupiter's Trojans, Retrograde and Prograde Irregular Satellites.
Summary

✦ Satellites at all four Solar System giant planets
  ✦ barely bound, \(\sim 0.1-0.5\) Hill radii semi-major axes
  ✦ highly eccentric, \(\sim 0.1-0.8\)
  ✦ more retrograde satellites than prograde ones
  ✦ collisional families
  ✦ relatively flat size distribution
Capture + Evolution
Nice model capture

Irregular satellites and Trojans likely captured at the same time

Difference is due to Gyrs of collisional evolution

Bottke et al 2010
Bottke et al. 2010

Cum. Number vs. Diameter (km) for different times:
- Time = 0 My: Obs. Retrograde, Model Prograde
- Time = 10 My: S = 0.61, 1.07
- Time = 40 My: S = 0.49, 0.73
- Time = 500 My: S = 0.31, 0.38
- Time = 1000 My: S = 0.26, 0.37
- Time = 1500 My: S = 0.20, 0.19
- Time = 3883 My: S = 0.07, 0.08
Why model irregulars?

- Fomalhaut b’s odd spectrum
- Possibility of detection around other stars
- Solar System
  - Validation/Comparison
  - Visible dust?
- Fate of dust? - e.g. Iapetus
One way to model irregulars

- “Collisional cascade” size distribution (fixed)
  - Mass in big bodies, surf. area in small bodies
- Mass reservoir of large objects depletes over time
- Debris disk-like collision rate - $n \sigma v$
Collisions faster and more frequent, swarm decays quickly

\[ R_{cc} \propto \frac{M_{\text{tot}} M_*^{1.38} f_{v_{\text{rel}}}^{2.27}}{Q_D^{0.63} \rho D_c M_{\text{pl}}^{0.24} (a_{\text{pl}} \eta)^{4.13}} \]

Collisions slower and less frequent, swarm decays slowly
surveys have searched for hot dust around Sun-like stars (main-sequence F, G, or K stars) by looking for a 25/C22 m flux in excess of photospheric levels using the Infrared Astronomical Satellite (IRAS; Gaidos 1999), the Infrared Space Observatory (ISO; Laureijs et al. 2002), and Spitzer (Hines et al. 2006; Bryden et al. 2006). All concluded that only 2% of these stars have hot dust with infrared luminosities \( L_{IR}/L_? > 10^4 \), finding a total of three candidates. Other hot dust candidates exist in the literature; however, some IRAS excess fluxes have turned out to arise from chance alignments with background objects (e.g., Lisse et al. 2002), including the candidate HD 128400 from the hot dust survey of Gaidos (1999) (B. Zuckerman 2006, private communication). Thus, confirmation of the presence of dust centered on the star using ground- and space-based mid-IR imaging is vitally important (R. Smith et al. 2007, in preparation). The tally of confirmed hot dust sources now stands at seven, and these are summarized in Table 1, which also gives the estimated radial location of the dust based on fitting of the spectral energy distribution (SED) of the excess emission; for all stars the dust is predicted to lie at <10 AU.

While the frequency of the presence of such emission is low, there is as yet no adequate explanation for its origin and why it occurs in so few systems. Analogy with the solar system suggests that these are systems in which we are witnessing the collisional grinding down of atypically massive asteroid belts. However, other scenarios have also been proposed in which the dust is transient, having been produced in some stochastic process. Such a process could be a recent collision between two massive protoplanets in an asteroid belt (Song et al. 2005), the sublimation of one supercomet (Beichman et al. 2005), or the sublimation of a swarm of comet nuclei, possibly scattered in from several tens of AU in an episode analogous to the period of late heavy bombardment (LHB) in the solar system (Gomes et al. 2005).

Fig. 2.—Collisional evolution of a planetesimal belt with parameters similar to the nominal model of DD03 [\( r = 43 \text{ AU}, \quad dr = 15 \text{ AU}, \quad D_c = 2 \text{ km}, \quad f(e; I) = 0.1, \quad e/I = 1, \quad Q_{D} = 200 \text{ J kg}^{-1}, \quad M_{tot}(0) = 10 M_{\odot} \text{ A0 star} \] showing the effect of changing the following parameters: starting disk mass \( M_{tot}(0) \) (top left), disk radius \( r \) (top right), collision velocity \( v_{rel}/v_{k} \) (middle left), maximum planetesimal size \( D_c \) (middle right), and stellar spectral type (bottom left). These plots can be directly compared to Figs. 1f of DD03.
"Stranding"

- Number > size
- ~few
- Size
Applications: Solar System
Idea

✦ Test/validate our model against known irregulars
✦ Are there interesting implications?
  ✦ Dust visible?
  ✦ Where does dust go?
✦ What could be done next?
The figure illustrates the distribution of the number of objects (n) as a function of size for different planets:

- **Jupiter** with \( N_w = 6 \) and \( \alpha = 1.0 \)
- **Saturn** with \( N_w = 2 \) and \( \alpha = 1.3 \)
- **Uranus** with \( N_w = 5 \) and \( \alpha = 1.2 \)
- **Neptune** with \( N_w = 4 \) and \( \alpha = 8.0 \)

The plot shows the model predictions for these objects, with the size on a logarithmic scale on the x-axis and the number of objects on a logarithmic scale on the y-axis.

The term "irregulars" refers to the smaller objects that do not fit into the regular patterns observed in the distribution.
What about the dust?

- A simple model suggests dust is detectable

- Dust mass - derive mean size distribution slope
- Size/shape - grain dynamics, sizes, properties
Saturn’s cloud?

Phoebe ring observations

Two off-target observations (Kiviuq ‘off’ and Phoebe ‘off’) illustrate typical observations. One of them ultimately strikes the dark leading face of Iapetus.

In February 2009 we used the Spitzer Space Telescope’s Multiband Imaging Photometer (MIPS) to scan regions near Phoebe’s orbit to search for a broad debris ring. Mosaics produced from these mid-infrared scans (IAPETUS East and IAPETUS West) centred 44 R_S (MIPSON) and at a substantially lower signal-to-noise ratio at 41 R_S (MIPSON 70). At the closest point to Saturn, the edges of the ring extend outward until they fade from view at five to ten planetary radii.

Dynamical considerations suggest that the dominant perturbation force acting on particles up to tens of micrometres in size is Saturn’s gossamer rings. Source satellites continuously supply the dust, which is sub-observer in size and it induces strong oscillations in orbital motion of Phoebe along its orbit. One views Saturn’s largest ring from Saturn’s, but because the moon’s greatest orbital tilts occur only when apocentres are in Saturn’s orbital plane, the ring is overwhelmed by scattered light in most observational directions.

We have conducted numerical simulations of the evolution of Saturn’s outer ring. As the outer ring dissipates, the moon’s orbital motion becomes more relaxed. The moon’s orbit around Saturn at an average distance of 60,330 km. The ring’s vertical thickness of 40 R_S is comparable to that of Jupiter’s broad sheets of dust, of thousands of years, producing a vertically extended torus with a depth of the ring is then simply the ratio of these two intensities:

\[ \frac{I_{\text{ring}}}{I_{\text{background}}} \]

A close match to the MIPSON mosaic span radii from 128 R_S (Saturn’s radius) to 207 R_S (Saturn’s radius). Phoebe’s ring also appears as a bright emission feature centred in mosaics produced from scans at 24 m and at 24 m (Spitzer Program 03582, principal investigator T. Grav). A serendipitously in the background of photometric observations of regions near Saturn, and a solid wall of them would emit with intensity for bright icy grains at 70 K.

For rings supplied by inclined satellites, the ring is overwhelmed by scattered light in most observational directions. Particles launched from Phoebe share the same orbital inclination as Phoebe itself and have nearly the same orbital period. Particles launched from Phoebe share their orbital period with Phoebe itself and have nearly the same orbital period. Size and density of the ring depend on the source satellite and on the particle size distribution of the source.

Particles with albedo 0.2 and emissivity 0.8 will have equilibrium temperature 85 K. The filling factor or line-of-sight optical depth would be an order of magnitude greater for bright icy grains at 70 K.
Saturn’s cloud?
Uranus’ cloud?

- Map 1deg square field around Uranus with Herschel SPIRE (250, 350, 500um)
- Observe field twice, second time *one year later* to remove same background signal
Fate of dust?

- Collision dominated
  - high eccentricity
  - hit planet/leave
- PR dominated
  - spiral in to planet
  - may hit regular satellites

\[ N > \text{size} \]

\[ P_{\text{rad}} \quad P-R \]

\[ D_{\text{min}} \quad \text{Size} \]
More work...

- What are the minimum grain sizes? $D_{\text{min}}(a,e,i,\text{etc.})$
- What does a realistic cloud look like?
- Is the Phoebe ring unique/special?
- Where do grains go and when?
- What can we learn from regular satellites?
  - Constrain model of grain accretion and rotation history with observed surface characteristics?
Grain orbits are complex!

Hamilton 1996
Applications: Extrasolar planets
Idea

- Planets being discovered by imaging
  - i.e. planets can have wide orbits

- Can low-mass (faint) planets be found if they have dust clouds?
HR 8799bcde

1 November 2009, L’ band

Marois et al 2009
Su et al 2009

4 planets
- debris disk
- ~60 Myr old
- 40pc

**Parameters in the Preferred Model**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Inner Warm Disk (warm)</th>
<th>Planetesimal Disk (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma(r)$</td>
<td>$\sim r^0$</td>
<td>$\sim r^0$</td>
</tr>
<tr>
<td>$R_{in}$ (AU)</td>
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<td>90</td>
</tr>
<tr>
<td>$R_{out}$ (AU)</td>
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<td>300</td>
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<td>$a_{min}$ (µm)</td>
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<td>10</td>
</tr>
<tr>
<td>$a_{max}$ (µm)</td>
<td>4.5</td>
<td>1000</td>
</tr>
<tr>
<td>$M_d$ ($M_\oplus$)</td>
<td>$1.1 \times 10^{-6}$</td>
<td>$1.2 \times 10^{-1}$</td>
</tr>
<tr>
<td>$f_d = L_{IR}/L_*$</td>
<td>$2.2 \times 10^{-5}$</td>
<td>$7.5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Fomalhaut, a bright star 7.7 parsecs (25 light-years) from Earth, harbors a belt of cold dust with a size and mass similar to our Kuiper Belt and can be imaged directly from the ground. Detection of Fomalhaut b, a Neptune-sized planet orbiting within the dust belt, confirms the existence of a planetary system around another sun. The planet is seen to be directly illuminated by its host star, allowing its demography to be studied in detail. The dust belt is inferred to have a radial extent of 114.2 AU, consistent with the location of the inner edge of the belt and the observed stellar proper motion across the sky. The motion of Fomalhaut b therefore appears to be nested within the dust belt and shows that the planet is physically associated with the dust belt.

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Extrasolar swarm evolution

HST  JWST

\[
\begin{align*}
F_{\text{Dust}} & \\
F_{1\text{MJ}} & \\
\end{align*}
\]

\[\lambda (~\mu\text{m})\]

\[F_{\nu}\] (Jy) at 10pc

Thursday, 17 February 2011
HST/JWST visibility of a swarm around a $1M_{\text{Jup}}$ planet
HST/JWST visibility of a swarm around a 20$M_{\text{Earth}}$ planet
Implications

- Swarms visible if captured populations large (~Moon mass)
- Swarms brightest when young
- Swarms most visible when on wide orbits (large Hill spheres)
- Scattered light better than thermal (resolution)
- Low-mass planets still detectable via their satellite swarms
Applications:
Fomalhaut b
Fomalhaut's disk

Disk offset from star position, sharp inner edge

Quillen 2006 prediction of planet at 119AU with e~0.1

*Kalas et al 2005, 2008*
Fomalhaut b’s spectrum could be scattered light
Idea

- Spectrum is light scattered from a dust cloud
  - (instead of Kalas $20R_{Sat}$ ring model)

- Attempt to find a model that can survive for 200Myr and is consistent with constraints.
dynamical max mass \( \sim 3 \, M_{\text{Jup}} \)

Chiang et al 2008; Kalas et al 2008
Open Questions

- How did Fom b get there?
- How did it capture the satellites?
- Is the orbit really nested within the debris ring?
Summary

✦ SS Irregular satellite populations still evolving
✦ Non-gravitational forces set the fate of dust
✦ Dust from collisions may be detectable
  ✦ Clouds around SS giant planets?
  ✦ Help detection of extrasolar planets?
  ✦ Fomalhaut b?
✦ Lots of details to follow-up...
Extras
Many studies have suggested that dark material migrating inward from the rings is the origin for dark material on the surfaces of all three. Dynamical studies predict that small irregular saturnian satellites have struck Phoebe several times over the age of the Solar System, providing known historic sources of material, much of which remains in the ring today. The amount of dusty material currently in the ring is enough to cover its long-term average, the accumulation rate is about 4000 times Phoebe's mass. To apply this figure to other assumed particle size distributions occurs first. The rate of mutual collisions depends on the size of the particles. This force brings all centimetre-sized and larger particles to Iapetus and Titan unless mutual particle collisions occur first. The rate of mutual collisions depends on the size of the particles.

Assuming (1) that Iapetus intercepts all this material and (2) that the ring population is currently near its long-term average, the accumulation rate is about 4000 times Phoebe's mass. To apply this figure to other assumed particle-size distributions, a ring composed entirely of 10 μm grains, the smallest that do not quickly reach Iapetus' orbit, would have number density expected for a distribution of particle orbits with similar inclinations. Re-radiation of absorbed sunlight exerts an asymmetric pressure gradient that pulls the outermost boundary of the ring inwards, with smaller percentages striking Hyperion. To reach a conservative separation of the two peaks increases with radial distance from Saturn. The large spike near the peak of the blue profile is produced by the bright background galaxy readily visible in the MIPSON scan. The observed flux (MJy sr⁻¹) over the course of a few frames and do not occupy a fixed location on the sky. These glints change geometry and brightness from frame to frame, as expected from a bright out-of-field source reflecting off different portions of the sky.
Ring crossing?

\[ \eta = R_{\text{dust}} (R_{\text{Hill}}) \]

- Unstable
- Resolved
- Optically thick

\[ \eta = 0.001 \]
\[ \eta = 0.01 \]
\[ \eta = 0.1 \]

\[ M_{\text{pl}} (M_{\text{Earth}}) \]