IRREGULAR SATELLITES IN THE CONTEXT OF PLANET FORMATION

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Received: 15 March 2004; Accepted in final form: 20 October 2004

Abstract. All four giant planets in the solar system possess irregular satellites, characterized by large, highly eccentric and/or highly inclined orbits. These bodies were likely captured from heliocentric orbit, probably in association with planet formation itself. Enabled by the use of large-format digital imagers on ground-based telescopes, new observational work has dramatically increased the known populations of irregular satellites, with 74 discoveries in the last few years. A new perspective on the irregular satellite systems is beginning to emerge. We find that the number of irregular satellites measured to a given diameter is approximately constant from planet to planet. This is surprising, given the radically different formation scenarios envisioned for the gas giants Jupiter and Saturn compared to the (much less massive and compositionally distinct) ice giants Uranus and Neptune. We discuss the new results on the irregular satellites and show how these objects might be used to discriminate amongst models of giant planet formation.

Keywords: satellites, Kuiper Belt, gas giant, ice giant, planet formation

1. Introduction

The irregular satellites of the planets are broadly distinguished from their regular counterparts by having large, highly eccentric and/or highly inclined orbits. Satellite accretion in a circumplanetary disk is unable to produce the extreme orbits of the irregular satellites, particularly the numerically dominant objects which follow retrograde trajectories about their parent planets. For this reason, the irregular satellites have long been recognized as likely products of the capture of bodies that were formed elsewhere and were previously in heliocentric orbit (Kuiper, 1956).

As with other definitions in the solar system (e.g., planet vs. Kuiper belt object, asteroid vs. comet) a single definition of the term “irregular satellite” is not agreed upon. The empirical definition as employed here (large, eccentric and/or inclined orbits) is the most simple and probably the most useful. Nesvorny *et al.* (2003) have defined irregulars as those satellites whose orbital planes precess strongly under the influence of solar tides. Fortunately, the two definitions yield essentially identical lists of irregular satellites. The main exception is Neptune’s satellite Triton, which is excluded by the Nesvorny definition because it is close to its planet and relatively immune to strong solar perturbations but which meets the empirical definition of an irregular satellite because its motion is retrograde (inclination = 156.8 degrees).

Space Science Reviews **114:** 407–421, 2004.

It is clearly a captured object but its small planetocentric distance and its extraordinary size (the diameter of 2700 km is an order of magnitude larger than the next largest irregular) separate it from the other irregulars in important ways. We will not consider it further here.

The number of known irregular satellites of the planets increased slowly through the 20th century, mostly in response to surveys conducted diligently using photographic plates. At Jupiter, for example, the irregular satellite total rose following the initial discovery of J6 Himalia in 1904 to only 9 such objects by the end of the century. Detailed physical observations exist for only one irregular satellite: Saturn's Phoebe was mapped at high resolution by the Cassini spacecraft in June 2004 (Figure 1). While physical observations remain limited, an unprecedented wave of satellite discovery has resulted from the use of wide field charge-coupled device cameras on moderate to large aperture telescopes. Fifty of the 74 recent discoveries have been made by us on Mauna Kea (Sheppard and Jewitt, 2003, see `http://www.ifa.hawaii.edu/∼sheppard/satellites/`) with most (46) of these at Jupiter. The number of Jovian irregulars is currently 55 (as of 2004 October 20) while irregular satellites have been identified around all four giant planets (Gladman *et al.*, 1998; 2000; 2001; Holman *et al.*, 2004; Sheppard and Jewitt, 2004). Observational programs to detect irregular satellites are challenging partly because of the faintness of most such objects but also because of the large areas of sky which must be searched. The region in which orbits are potentially stable is of a scale comparable to the Hill radius, defined as

$$r_{\mathrm{H}} = a\left(\frac{m_{\mathrm{P}}}{3M_{\odot}}\right)^{1/3} \tag{1}$$

where a is the orbital semimajor axis of a planet of mass m_{P}, and $M_{\odot}$ is the mass of the sun. Values of r_{H} are given in Table I for each giant planet, in both linear and angular units. At the time of writing, the Hill spheres have been surveyed to near completeness to limiting red magnitude $m_R \sim 23$ at Jupiter, $m_R \sim 24$ at Saturn, and $m_R \sim 26.1$ at Uranus, while Neptune is less complete to $m_R \sim 25.5$.

The purpose of this short paper is to draw attention to the new work and to point out its likely relevance in constraining modes of satellite capture and giant planet formation. Models of gas and ice giant planet formation must be at least consistent with the known properties of the irregular satellite populations. It is not obvious that all proposed models meet this basic requirement. One reason is that the formation models were not specifically constructed to fit the newly-determined properties of the irregular satellite populations of the giant planets. We do not doubt that some of the models can be bent to fit the new irregular satellite data, as discussed below. It is the degree of bending which, we assert, provides an interesting and unexpected way to judge the models.

Figure 1. Saturn's $\sim$200 km diameter irregular satellite Phoebe, as imaged by the Cassini Imaging Science Subsystem in June 2004. This is the only irregular satellite for which highly-resolved physical observations are available. The surface is densely cratered up to sizes approaching the catastrophic disruption limit of the body. Bright ice streaks are visible on some of the steeper slopes (e.g. on the sun-facing wall of the largest visible crater). Image courtesy of NASA and the ISS team.

TABLE I
Numbers of Irregular Satellites

Planet	R a)	Δm b)	$N_{\rm i}$ c)	$N_{\rm i}^{23}$ d)	N_*^{23} [deg] e)
Jupiter	5	0	55	36	36
Saturn	10	2.6	14	8	10
Uranus	20	5.9	9	4	3
Neptune	30	7.6	$7^{\rm f}$	$2^{\rm f}$	1

a) Average Planet-Sun distance in AU

b) Magnitude decrement $\Delta m = 5\log_{10}[R(R-1)/(R_{\rm J}(R_{\rm J}\text{-}1)]$, where $R_{\rm J}$ is the Sun-Jupiter distance

c) Total number of reported irregular satellites

d) Number of known irregular satellites with $m_R \leq 23$

e) Number of irregular satellites with $m_R \leq 23$ expected if each planet holds a satellite population equal to that at Jupiter

f) If Triton is not counted, $N_{\rm i} = 6$ and $N_{\rm i}^{23} = 1$

2. Relation to Planet Formation

A simple chain of reasoning links the capture of the irregular satellites to the epoch of planet formation.

1. The orbits of the irregular satellites, especially the retrograde orbits, cannot be plausibly explained as products of accretion in circumplanetary disks.
2. Such orbits are instead likely to be produced by capture from heliocentric orbits.
3. While temporary capture is easy, permanent capture from heliocentric orbit requires energy dissipation to convert an initially unbound orbit into a bound one.
4. The present-day solar system offers no adequate source of energy dissipation and, therefore, the captures must have occurred at an earlier epoch when dissipation was present.
5. The gross properties of the solar system have changed little since the era of planet formation. Therefore, the irregular satellites were probably captured at very early times, contemporaneous with planet formation.

The relationships between the various small-body populations of the solar system are shown in Figure 2. There, dotted lines emphasize that the irregular satellites, like the Trojan asteroids, have no dynamically plausible source in the modern solar system. By placing satellite capture at very early times, the irregulars open a potentially valuable new window on the planet formation process.

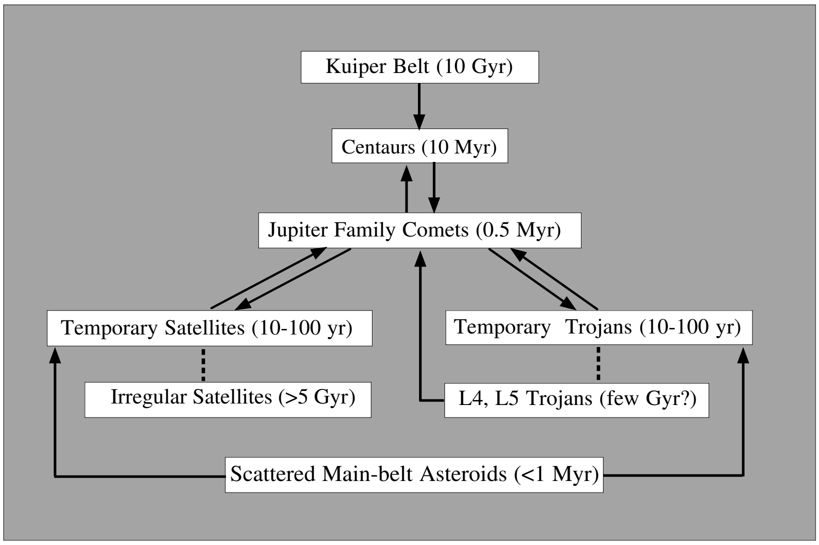

Figure 2. Schematic diagram showing relationships between various small body populations of the solar system. Currently active pathways from the major reservoirs in the Kuiper Belt and main asteroid belts are shown by solid arrows. The approximate dynamical lifetimes of the various populations are indicated. Dotted lines mark currently inactive pathways to the irregular satellites and 1:1 resonators. The dotted pathways may have been active in the early solar system, in the presence of energy dissipation. Figure from Jewitt *et al.* (2004).

2.1. SOURCES OF DISSIPATION

Three potential sources of dissipation in the early solar system have been discussed in the literature in the context of the irregular satellites.

1. Satellite capture could have been aided by dissipation due to gas drag (Pollack *et al.*, 1979). Before reaching their final equilibrium configurations, the gas giants are thought to have sustained transient, bloated gaseous envelopes. Gas drag exerted on solid bodies passing through such envelopes could lead to one of three distinct dynamical outcomes. Small bodies, with a high ratio of cross-sectional area to mass, could be decelerated from heliocentric orbit to spiral into the body of the growing planet. Large bodies, with a small ratio of cross-section to mass, would pass through the envelope with little change in momentum. Intermediate sized bodies could be slowed just enough to avoid the death-spiral into the growing planet but enough to be captured by the planet. The sudden collapse of the envelope would leave some such objects suspended in irregular type orbits (Pollack *et al.*, 1979). One suggested observational signature of capture by gas drag would then be a narrow size distribution corresponding to those objects for which deceleration was “optimal”. (Subsequent collisions, however, might modify the size distribution by breaking-up the captured bodies into smaller fragments, so concealing the tell-tale narrow size range expected from gas drag capture).

2. The sudden mass-growth of the planets leads to a second mechanism of capture, known as "pull-down" capture (Heppenheimer and Porco, 1977). In pull-down capture, a heliocentric body moving at low velocity relative to the parent planet enters the Hill sphere through a Lagrange point. Residence in the Hill sphere would be temporary (with a timescale corresponding typically to tens or hundreds of years) but for the effect of the increasing mass of the growing planet. Provided the planetary mass increases on a timescale that is short compared to the residence time, this mechanism could lead to the permanent capture of any bodies in the vicinity of a giant planet. Very rapid (runaway) mass growth is expected in some models of gas giant formation.
3. Three-body interactions, both collisional and non-collisional, involving two small bodies moving in the vicinity of a massive planet could lead to capture of one of the objects (Colombo and Franklin, 1971; Weidenschilling, 2002). Fragments produced by energetic collisions could also be captured. Collisions between the known irregular satellites are rare (Nesvorny *et al.*, 2003) and the rate of collisions between the known irregular satellites and cometary nuclei is also negligbly small (Nakamura and Yoshikawa, 1995). Therefore, collisional capture could only work efficiently if the initial populations of small bodies were much larger than now observed. This is qualitatively consistent with independent evidence that the solar system underwent an early clearing phase in which the flux of interplanetary bodies was orders of magnitude higher than now (the so called "terminal bombardment"). It is also possible that the irregular satellites are the survivors of a once huge population of temporary satellites, stabilized by 3-body interactions.

3. New Observational Results

The Jovian system, because of its proximity, is observationally the best characterized and serves as a useful reference for comparison with less complete data available for the irregular satellites of the outer planets. This is evident from the inverse square law

$$p_R r^2 = 2.25 \times 10^{22} R^2 \Delta^2 10^{0.4 \Delta m_R}. \qquad (2)$$

which connects the radius, r (km), the geometric albedo, p_R, and the heliocentric and geocentric distances, R (AU) and Δ (AU) of the satellite to the apparent brightness. Here, Δm_R is the difference between the R-band magnitude of the Sun and of the satellite. With $R \gg 1$ and substituting p_R = 0.04, this relation gives

$$r \sim \left[\frac{R}{5}\right]^2 10^{0.2(24-m_R)}. \qquad (3)$$

For example, Equation (3) shows that satellite surveys made to magnitude m_R = 24 reach limiting radii $r \sim 1$, 4, 16 and 36 km at Jupiter, Saturn, Uranus and Neptune,

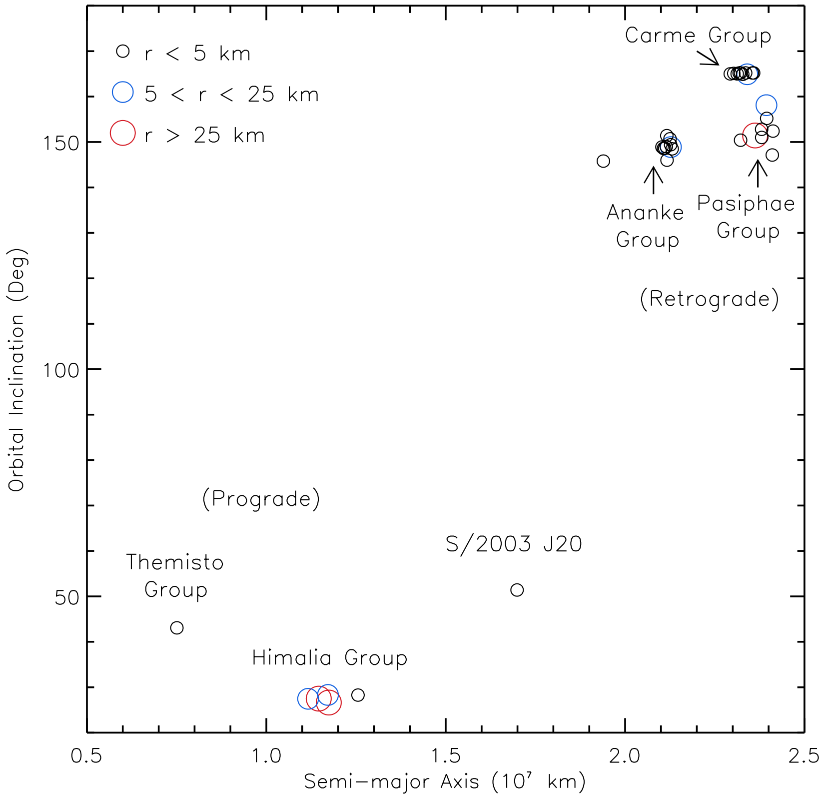

Figure 3. Distribution of the time-averaged orbital semimajor axes and inclinations of the Jovian irregular satellites. The sizes of the satellites are related to the sizes of the symbols, as shown. Only satellites observed on two or more oppositions have been plotted to ensure that the orbital elements are reliable. Note that 2.5×10^7 km corresponds to about 350 Jupiter radii and to about 0.17 AU. Elements were provided by Bob Jacobson of JPL and the figure is from Sheppard and Jewitt (2003).

respectively. For this reason we know of a large number of (mostly small) irregular satellites at Jupiter but only smaller numbers of larger objects at the other giant planets.

The new satellite discoveries, especially those at Jupiter, show evidence for clustering of the orbital properties (Figure 3). The velocity dispersion within each cluster is comparable to the gravitational escape velocity of the largest cluster member (Nesvorny *et al.*, 2003; Sheppard and Jewitt, 2003). This suggests an origin through collisional break-up of precursor bodies after their capture into planetary orbit. If so, Jupiter's irregular satellite clusters point to 6 or 7 precursor objects (3 prograde and 3 or 4 retrograde) with radii in the ∼1 km to ∼85 km range. Consistent with this interpretation are photometric measurements which show color differences between clusters and relative color uniformity within them (Rettig *et al.*, 2001; Grav *et al.*, 2003). Irregular satellites of the other giants are probably also dynamically clustered – Saturn with ∼4 clusters, Uranus with 2 or 3,

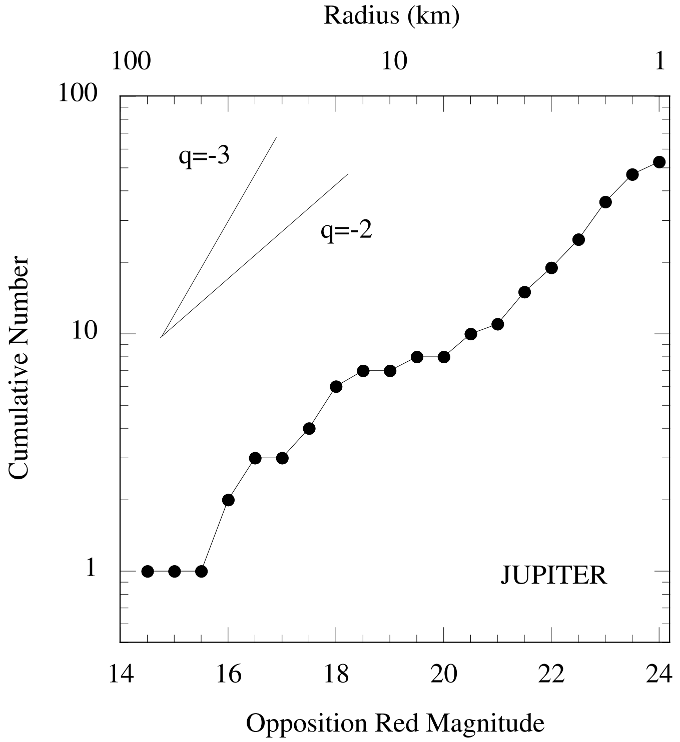

Figure 4. Cumulative number of Jovian irregular satellites as a function of opposition red magnitude, compiled from data available on 2004 February 5. Diagonal lines show the slopes expected if the differential size distribution is a power law with index q = -2 and q = -3. The overall satellite distribution resembles the q = -2 case, but the flattening between m_R = 18 and m_R = 20 shows that the satellite distribution does not follow a simple power law. The upper scale shows the effective circular radius computed on the assumption that the geometric albedo is p_R = 0.04.

Neptune with 3 (or 4 if Triton is counted) – but their known populations are smaller and the cluster parameters less well defined.

Figure 4 shows the cumulative number of Jovian irregular satellites as a function of apparent red magnitude, m_R. The corresponding radii from Equation (3) are shown on the upper x-axis of the figure. The data are believed to be complete to m_R = 23 – the turn-down in the curve in the last point at m_R = 24 may result from objects yet unfound. Note that the satellites are likely to be aspherical and that their magnitudes will vary as a function of rotational phase. This effect, which remains unquantified in the smaller satellites, is not accounted for in Figure 4. Diagonal lines in the Figure mark the brightness distributions that would be expected if the satellite radius distribution obeyed a simple differential power law

$$n(r)dr = \Gamma r^q dr \tag{4}$$

where r is the radius, Γ and q are constants. The satellite distribution is broadly similar to the q = -2 line, but clearly shows deviations from power-law behavior that are significant. In particular, the flattening of the cumulative distribution between magnitudes m_R = 18 and m_R = 20 (radii $6 \leq r \leq 16$ km) must reflect a true paucity of such objects in the Jovian irregular satellite population because the current surveys are essentially complete at these high brightness levels (c.f. Sheppard and Jewitt, 2003). The satellite size distribution is flatter than expected for a population in collisional equilibrium (the so-called Dohnanyi, 1969, distribution, for which $q \sim$ -3.5). We lack the statistics to accurately determine the size distribution within the individual dynamical clusters.

We combine the cumulative plot of Figure 4 with information about comparable satellite surveys to compare the irregular satellite populations of the four giant planets. In Table 2 we have listed the total number of irregular satellites for each planet, N_i, regardless of brightness, as well as N_i^{23} (the number having $m_R \leq 23$). (The data were taken from the compilation by the JPL solar system dynamics group at http://ssd.jpl.nasa.gov/. Listed V magnitudes were corrected to R magnitudes using $m_V - m_R$ = 0.5). We select m_R = 23 as a reference magnitude because each of the giant planets has been surveyed to this level and the populations of brighter satellites can be regarded as well known (certainly to within a factor ~2, probably better). With albedo p_R = 0.04, the effective radius would be r ~1.6 km (Equation 3). The column labelled N_*^{23} is the number of irregular satellites brighter than m_R = 23 that are expected if each giant planet possess an intrinsic population identical to that at Jupiter. This number is estimated by scaling the Jovian population for the greater distance of each planet. The magnitude decrement resulting from the greater distance is approximately

$$\Delta m = 5log_{10}\left[\frac{R(R-1)}{R_{\rm J}(R_{\rm J}-1)}\right] \tag{5}$$

assuming that the planets are observed at opposition. Here, $R_{\rm J} \sim 5$ AU is the average Sun-Jupiter distance. For example, Saturn with $R \sim 10$ AU has Δm = 2.6 mag. (Table II) and we read from Figure 4 that the number of irregulars with $m_R \leq$ (23.0 - 2.6) = 10, whereas the actual number is 8. The Table shows the astonishing result that

$$N_*^{23} \sim N_{\rm i}^{23}\ , \tag{6}$$

meaning that the irregular satellite data are consistent with the hypothesis that each of the four giant planets possesses an irregular satellite system like that observed at Jupiter. In other words, the number of irregular satellites per giant planet remains approximately constant (to within a factor of ~2) even as the planetary mass varies by a factor of about 20 from Jupiter to Uranus. (It could be argued that we should count satellite groups rather than individual satellites, since the groups probably represent the true numbers of initially captured bodies. Doing so gives the same result: each giant planet possesses a handful of satellite clusters, the largest members of which have $m_R \leq 23$, consistent with scaling from Jupiter using Equation 5). This result is remarkable, since there are no a-priori reasons why the irregular

TABLE II
Hill spheres of the giant planets

Planet	m_P [a]	a [b] [AU]	r_H [AU] [c]	r_H [deg] [d]
Jupiter	310	5	0.35	5
Saturn	95	10	0.43	2.8
Uranus	15	20	0.47	1.4
Neptune	17	30	0.77	1.5

[a] Planet mass in multiples of Earth's mass (6×10^{24} kg)
[b] Semimajor axis in AU
[c] Radius of Hill sphere in AU
[d] Projected radius of Hill sphere in degrees at opposition

satellite populations of the different planets should be at all similar, even to within order of magnitude.

To drive this core point home, we make it again in a different way in Figures 5 and 6. Figure 5 shows the cumulative number of irregular satellites of each planet brighter than a given apparent red magnitude. (Data for the plot were compiled from the various discovery IAU Circulars and Minor Planet Electronic Circulars, with corrections from V magnitudes to R magnitudes using V - R = 0.4, where necessary). Figure 6 shows the same satellite data as in Figure 5, but with the magnitudes corrected to the opposition heliocentric and geocentric distances of Jupiter using the offsets, Δm, listed in column 3 of Table II. Whereas the curves in Figure 5 are widely separated, those in Figure 6 substantially overlap, showing that the main differences between the statistics of the irregular satellites are artifacts of the different distances of the planets and the finite magnitude limits of the surveys used to study them. If the populations were exactly equal, all four curves in Figure 6 would overlap precisely. That they do not presumably results from real (but small) intrinsic population differences and from photometric corrections for rotation and phase-angle dependent scattering which we have neglected.

We briefly explore some of the consequences of the constancy of the irregular satellite populations.

4. Reconciliation with Giant Planet Formation Models

4.1. CORE ACCRETION

Jupiter and Saturn likely grew by runaway accretion of nebular hydrogen and helium onto a core of higher molecular weight material. Their transient gaseous envelopes are a plausible source of frictional energy dissipation by which the ir-

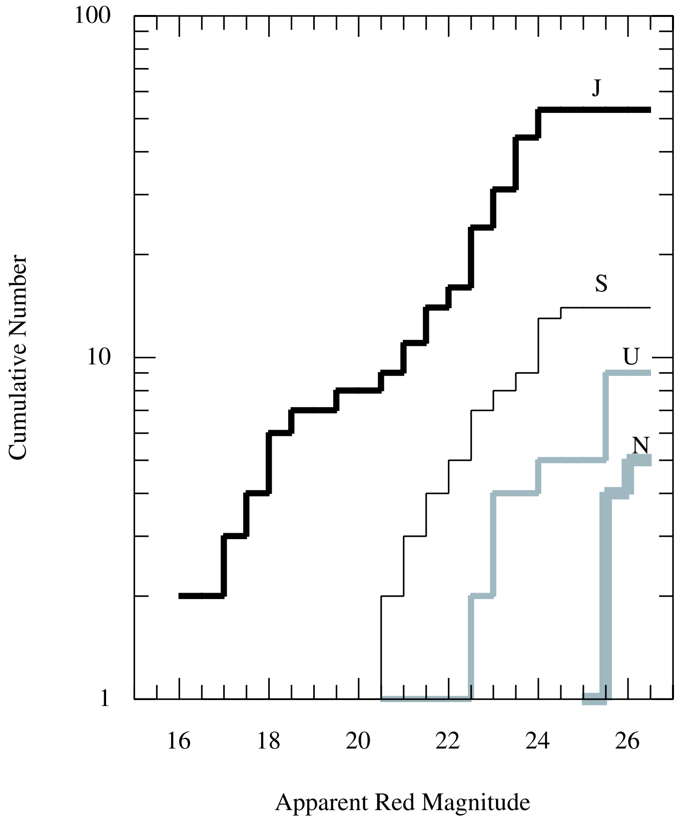

Figure 5. Cumulative numbers of irregular satellites brighter than a given apparent red magnitude (binned in 0.5 mag increments) for each of the four giant planets (J = Jupiter, S = Saturn, U = Uranus, N = Neptune).

regular satellites of these planets might have been captured (Cuk and Burns, 2003). The sudden increase of mass associated with runaway growth could also lead to pull-down capture of the irregular satellites. However, neither gas drag nor pull-down capture can explain the existence of comparable populations of irregular satellites of the ice giants Uranus and Neptune. The latter planets possess little excess hydrogen and helium and are not thought to have undergone dramatic runaway growth as did Jupiter and Saturn. Therefore, gas drag and pull-down capture offer implausible explanations for the existence of irregular satellites of Uranus and Neptune.

4.2. DISK INSTABILITIES

In some models spontaneous collapse of segments of disk (without the need for a high molecular weight core) can occur on extremely short timescales, perhaps as small as a few $\times 10^3$ years (e.g., Boss, 1997). Bodies with the $\sim$100 km size of the

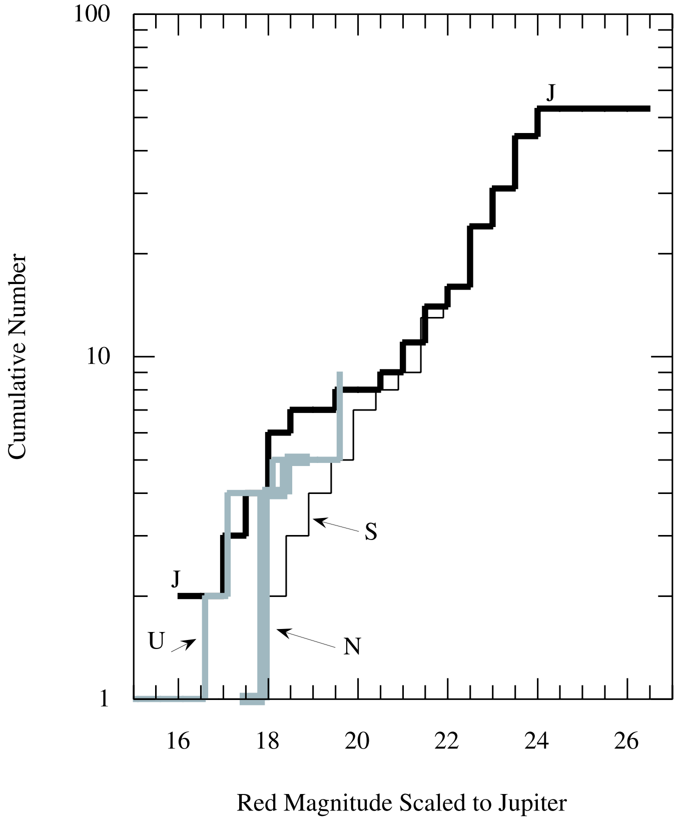

Figure 6. Same as Figure 5 but with the magnitudes of the satellites scaled to the opposition heliocentric and geocentric distances of Jupiter using the inverse square brightness law (see column 3 of Table II). Again, J = Jupiter, S = Saturn, U = Uranus, N = Neptune. The curves in Figure 5 have coalesced.

satellite precursors could not have grown on such short timescales and so would not have been available to be captured. In order to explain the prior existence of the irregular satellites one would need to delay the nebular collapse (i.e., require that the timescale for planetesimal accumulation in an unstable central disk be less than the timescale for gravitational collapse of the nebular gas as a whole). Perhaps this is possible, but it is not a featured result of the disk models of which we are aware. Moreover, disk instabilities cannot account for the highly non-solar (hydrogen and helium depleted) compositions of Uranus and Neptune.

4.3. ABLATION MODELS

To explain the ice giants Uranus and Neptune, Boss (2003) has advocated a model in which these planets are the remnants of $\sim 2\ M_J$ gas giants ablated by a sustained ionizing flux of photons from nearby OB type stars. Essentially, Uranus and Neptune formed like Jupiter and Saturn but, because of their great heliocentric distance and reduced shielding from ionizing photons by nebular gas, were ablated to their present structures. Decreasing planetary mass poses severe problems for the stability of the irregular satellites (if Jupiter's 310 $M_\oplus$ were whittled away to Uranus' 15 $M_\oplus$ then its irregular satellites would be lost to interplanetary space). One could conjecture that, if the ablation models are correct then the irregular satellites must have been captured at a later time. Even this is problematical, however, because the late stage ice giants would lack the extended gaseous envelopes needed for frictional capture, do not exhibit rapid mass growth needed for pull-down capture, and would not necessarily retain solid body retinues sufficient to guarantee multiple collisions. In short, within the context of the existing models for the origin of the irregular satellites, the satellite data do not appear compatible with the ablation model.

4.4. REARRANGEMENT MODELS

Thommes *et al.* (1999) suggested that Uranus and Neptune grew alongside the heavy cores of Jupiter and Saturn in the $\sim$4 to $\sim$10 AU zone. The ice giants failed to accrete much nebular hydrogen and helium (and therefore never attained gas giant status) as a result of being prematurely scattered out to the gas-poor regions of the outer solar system. Numerical simulations indicate that the irregular satellites of Uranus and Neptune could not survive this violent rearrangement of the solar system (Beauge *et al.*, 2002). Therefore, in the rearrangement models, the irregular satellites must have been captured after the orbits of Uranus and Neptune were circularized near their current locations. The problems then become the same as for the ablation models: there is too little gas to effect capture and too little mass-growth of the planets for capture by the pull-down mechanism. Instead, a plausible collisional origin for the capture of the irregular satellites could perhaps be constructed, given that the circularization of the orbits of the ice giants is due to their tidal interaction with a still massive planetesimal disk. In the simulations of Thommes *et al.* (1999) associated planetary bombardment continues for $\sim 10^7$ yr and this sets the timescale for collisional capture of the irregular satellites.

4.5. DISCUSSION

In stark contrast to Jupiter and Saturn, the ice giants hold only 2 or 3 $M_\oplus$ of hydrogen and helium gas from the nebula, offering greatly reduced opportunity for satellite capture by gas drag. Indeed, the efficacy of gas drag capture around the heavily gas-depleted ice giants has never been demonstrated. Furthermore, in the standard model, the ice giants grew steadily through the accretion of planetesimals with no pronounced mass runaway, so that pull-down capture of the satellites is also inviable. Instead, the existence of the irregular satellites of the ice giants is more compatible with a collisional or 3-body source of dissipation, since such a source requires no assumptions about the gas content or mass growth rate of the planet (Colombo and Franklin, 1971; Nesvorny *et al.*, 2003). The main requirement is a greatly enhanced density of precursor objects within the Hill spheres of the planets at the time of their formation. Little quantitative work has been done to estimate the capture rate to be expected from this process, although the work of Weidenschilling (2002) concerning the production of Kuiper Belt binaries is clearly relevant.

More puzzling is why the satellite populations of the four giant planets, measured to a given absolute magnitude or size, should be even remotely similar (c.f. Table II). We cannot exclude the possibility that the invariance of the number of irregular satellites, measured with respect to the planetary mass and mode of formation, is simply a coincidence. For example, satellites could have been captured by different processes at different planets (e.g., gas drag and/or pull-down at Jupiter and Saturn, by 3-body interactions within the Hill spheres at Uranus and Neptune) and, by chance, produce similar numbers of satellites. Another possibility is that the irregular satellites of all four giant planets were captured through collisional dissipation, the process which is least tightly coupled to the details of the planet growth mechanism. In this regard we note that the Hill spheres increase in size by a factor of $\sim$2 from Jupiter to Neptune (Table I) and that the associated volumes within which collisions might lead to capture increase by $2^3 \sim 10$. This partially compensates for the decrease in the collision rate expected from the decline in the density of the protoplanetary disk with radius and so could help produce a more shallow variation of satellite number from Jupiter to Neptune than would otherwise be expected.

Capture by gas-drag is the most-discussed model for the origin of the irregular satellites but the reasons for this prominence appear largely historical and are not compelling. Gas drag has not been shown to be effective around the ice giants, where substantial populations of irregular satellites are now known. Worse, the model offers few clear, observationally verifiable predictions for the properties of the irregular satellite systems (other than the strongly violated “prediction” that it should not be effective around planets having little gas, like Uranus and Neptune!). It therefore seems prudent to keep an open mind about the way (or ways) in which the irregular satellites were captured and more theoretical effort on the efficacy of capture by other processes seems warranted. We are especially intrigued by the possibility that 3-body interactions within the planetary Hill spheres could have been responsible for satellite capture and we encourage quantitative investigation of this scenario.

Acknowledgements

We thank Yan Fernández, Jane Luu and Toby Owen for comments. This work was supported by a grant to DJ from the NASA Planetary Astronomy Program.

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