# An abundant population of small irregular satellites around Jupiter

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**Irregular satellites have eccentric orbits that can be highly inclined or even retrograde relative to the equatorial planes of their planets. These objects cannot have formed by circumplanetary accretion, unlike the regular satellites that follow uninclined, nearly circular and prograde orbits[1]. Rather, they are probably products of early capture from heliocentric orbits[2–5]. Although the capture mechanism remains uncertain, the study of irregular satellites provides a window on processes operating in the young Solar System. Families of irregular satellites recently have been discovered around Saturn (thirteen members, refs 6, 7), Uranus (six, ref. 8) and Neptune (three, ref. 9). Because Jupiter is closer than the other giant planets, searches for smaller and fainter irregular satellites can be made. Here we report the discovery of 23 new irregular satellites of Jupiter, so increasing the total known population to 32. There are five distinct satellite groups, each dominated by one relatively large body. The groups were most probably produced by collisional shattering of precursor objects after capture by Jupiter.**

Starting with JVI Himalia in 1904, most twentieth-century discoveries of planetary satellites were made using photographic plates. The recent development of more sensitive, large-scale charge-coupled device (CCD) detectors has refreshed the subject by enabling a new wave of satellite discovery. We have begun a systematic survey designed to assess the properties of the Jupiter satellite population. Bound satellites are confined to the region of gravitational influence of Jupiter, known as the Hill sphere. The Hill sphere radius is

$$r_{\mathrm{H}} = a_{\mathrm{J}} \left[\frac{m_{\mathrm{J}}}{3M_{\odot}}\right]^{1/3} \qquad (1)$$

where $a_{\mathrm{J}}$ and $m_{\mathrm{J}}$ are the semi-major axis and mass of Jupiter and $M_{\odot}$ is the mass of the Sun. With $a_{\mathrm{J}} \approx 5\,\mathrm{AU}$ and $m_{\mathrm{J}}/M_{\odot} \approx 10^{-3}$, Jupiter's Hill radius is $r_{\mathrm{H}} \approx 0.35\,\mathrm{AU}$ ($\sim$740 Jupiter radii) corresponding to a circle of radius 4.7 degrees in the plane of the sky, when viewed at opposition (area $\approx$70 square degrees). Jupiter's Hill sphere, as seen in the plane of the sky, is 2.5 times the area of Saturn's and ten times the area of Uranus's and Neptune's. We surveyed the region around Jupiter from about 0.15 to 4.5 degrees ($0.03 \leq r/r_{\mathrm{H}} \leq 0.95$), eventually finding 23 new satellites[10,11] (Fig. 1 and Table 1). Follow-up astrometry over periods of months was used to confirm association with Jupiter, making use of orbit-fitting calculations by B. Marsden and R. Jacobson. Satellites in retrograde orbits have semi-major axes that are all less than $0.47r_{\mathrm{H}}$ ($0.27r_{\mathrm{H}}$ for the progrades) as is true for all known irregular satellites[6]. Some Jupiter satellites currently have apojoves up to $0.65r_{\mathrm{H}}$.

At present it is practically impossible for Jupiter to capture satellites permanently because no efficient dissipation mechanism exists[2]. Satellite capture could have occurred more easily towards the end of Jupiter's formation epoch owing to gas drag from an extended Jupiter atmosphere, the enlargement of the Hill sphere caused by the planet's mass growth and/or higher collision probabilities with nearby small bodies[3–5]. If so, satellite capture occurred on the same (short but uncertain) timescale as Jupiter's growth, probably in the range $10^4$ to $10^7$ yr (refs 12, 13). The known irregular satellites are stable over the age of the Solar System, although strongly influenced by solar and planetary perturbations[14].

The sizes of the new satellites can be estimated assuming geometric albedos of 4%, as measured for satellites Himalia and Elara[15]. We calculate radii ($r$) from about 1 to 4 kilometres (Table 1). Earlier observations appeared to show that the irregular satellites followed a very shallow size distribution[16] with $q \approx 2$, where $n(r)\,\mathrm{d}r \propto r^{-q}\,\mathrm{d}r$ is the differential power-law radius distribution with $n(r)\,\mathrm{d}r$ the number of satellites with radii in the range $r$ to $r + \mathrm{d}r$. Our observations suggest that the distribution is not well described by a single power law. We confirm $q \approx 2$ for the larger satellites ($r > 10\,\mathrm{km}$) but find a steeper slope ($q \geq 3.5$) for those with $r < 4\,\mathrm{km}$. There is a strong flattening in the size distribution between radii of 10 and 4 km (apparent red magnitude $19 \leq m_{\mathrm{R}} \leq 21.5$). For comparison many asteroid families have $q \geq 4$ (see ref. 17), collisional equilibrium gives $q \approx 3.5$ (see ref. 18), while nonfamily asteroids show $q \approx 2.0$ to 2.5 (see ref. 19). A few large satellites are accompanied by many smaller ones

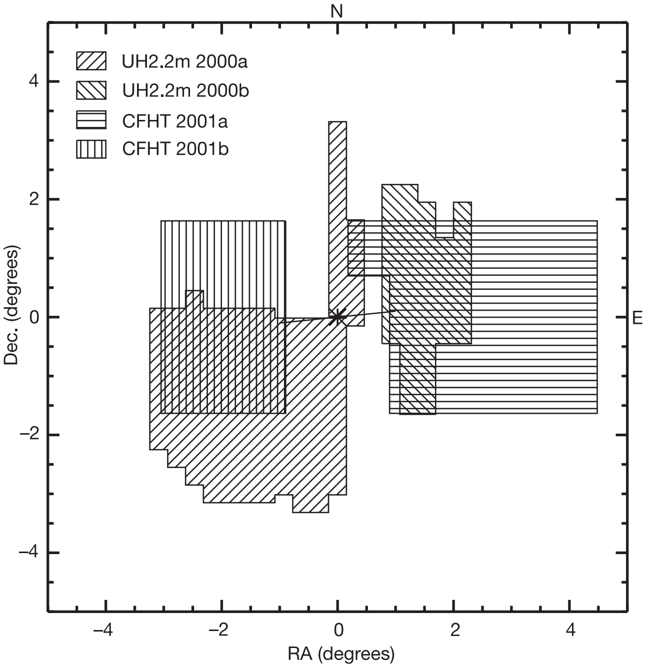

**Figure 1** The area searched around Jupiter for satellites. Satellites were identified by their characteristic, Jupiter-like proper motions. We used the University of Hawaii 2.2-m telescope (UH2.2m) with its 8k CCD camera ($18.4' \times 18.4' \approx 0.094$ square degrees field-of-view) during late November 2000 and found ten new satellites (S/2000 J1 to S/2000 J10) (see ref. 10). In mid-December 2001 we used the Canada–France–Hawaii 3.6-m telescope (CFHT) with the facility 12k CCD camera ($43' \times 28' \approx 0.33$ square degrees) and discovered eleven new satellites (S/2001 J1 to S/2001 J11) (see ref. 11). An additional two satellites were discovered in the survey fields during follow-up observations, for a total of 23 new satellites. The thick black line shows the orientation of the ecliptic during the observations. All the search fields of 2000 were examined both by visual blinking and a computer algorithm written by E. Magnier. For the 2001 fields we used a computer program written by J. Kleyna along with visual blinking to find the satellites. A measure of completeness of our survey is provided by our serendipitous detections of previously known satellites. We detected all six of the then-known nine irregular satellites of Jupiter that were in our fields in November 2000. In December 2001 we detected 12 of the 15 irregulars predicted to lie within the survey area, with the other three undetected because they were near bright stars. Because weather factors varied over the different nights we split the survey up into four parts. UH2.2m 2000a: Total area searched was 12.0 square degrees to a limiting *R*-magnitude of about 21.5 with one new satellite discovered. UH2.2m 2000b: 4.4 square degrees, $m_{\mathrm{R}} \approx 22.5$, nine new satellites. CFHT 2001a: 12.4 square degrees, $m_{\mathrm{R}} \approx 23.2$, ten new satellites. CFHT 2001b: 6.7 square degrees, $m_{\mathrm{R}} \approx 22.5$, one new satellite. Both S/2000 J11 and S/2002 J1 were discovered while recovering other satellites and thus are not included in the above survey statistics.

($r < 4$ km), the latter having a size distribution similar to that of the main-belt asteroid families. By extrapolation, we estimate that, within a factor of two, Jupiter possesses approximately 100 irregular satellites with $r \geq 0.5$ km, corresponding to about 24th magnitude. We also find that the completeness limit for satellites at Jupiter is currently $r \approx 3$ km ($m_{\mathrm{R}} \approx 21.5$).

The mean orbital inclination and mean semi-major axis distributions show two distinct prograde groups, here named the Himalia and Themisto groups after the largest object in each (Fig. 2). Clumping in Fig. 2 suggests that the retrograde satellites comprise at least three groups (we denote these the Pasiphae, Ananke and Carme groups). The absence of objects with intermediate inclinations $55° < i < 130°$ may be a result of the Kozai effect[14], which couples variations in inclination and eccentricity and forces highly inclined satellites to dip into the galilean satellite region, where they are removed by collisions.

These dynamical groups suggest origin by the break-up of multiple parent objects. Each retrograde group contains one large object ($r > 14$ km) along with several smaller ones ($r < 4$ km). Sinope, the only other large satellite, may currently be the only known member of a fourth group or it may be part of the Pasiphae group. In support of a collisional origin, we note that the dispersion velocities[20] between members of each group are comparable to the escape velocity of the largest body ($\sim 30$ m s$^{-1}$ for each retrograde group). Velocity differences between objects in different groups ($>200$ m s$^{-1}$), probably from different parents, are much larger than the escape velocity from any member. Also, observations of the brightest irregulars show that the retrogrades are redder and more spectrally diverse than the Himalia prograde group[21], consistent with the origin of the former from the break-up of four different parent objects.

The sizes of the parent bodies can be estimated by combining the volumes of the satellites within each group. We infer that the Ananke group parent body had a radius of about $r_{\mathrm{p}} \approx 14$ km while the ratio of the mass in the largest fragment to the mass of the parent is $M_{\mathrm{l}}/M_{\mathrm{p}} \approx 0.98$. For the Carme group we find $r_{\mathrm{p}} \approx 23$ km with $M_{\mathrm{l}}/M_{\mathrm{p}} \approx 0.99$ and for the Pasiphae group $r_{\mathrm{p}} \approx 30$ with $M_{\mathrm{l}}/M_{\mathrm{p}} \approx 0.99$ (or 0.79 if including Sinope). For the prograde Himalia group we find $r_{\mathrm{p}} \approx 89$ km with $M_{\mathrm{l}}/M_{\mathrm{p}} \approx 0.87$. Satellite groupings with $M_{\mathrm{l}}/M_{\mathrm{p}} \approx 1$ suggest collisional origin by shattering with a projectile barely above the disruption threshold. Such high mass ratios are atypical of asteroid families[17], although the Vesta asteroid family, with $M_{\mathrm{l}}/M_{\mathrm{p}} \approx 0.95$, may be similar[22] in suffering only minimal damage during its lifetime from relatively small impacts.

It is unlikely that the satellite groups were produced by the sole action of aerodynamic forces during capture, because self-gravity would prevent the fragments from dispersing[4]. Additionally, gas drag acting on the fragments would produce a size-dependent sorting of the orbits within each group[2,4,6]. No size versus orbital property correlations are seen in the groupings in the $\sim 1$ km to $\sim 100$ km size range. For these reasons we believe that the disruptions occurred after capture and after the dissipation of the gas left over from Jupiter's formation.

Fragmentation of the parent satellites could be caused by impact with interplanetary projectiles (principally comets) or by collision with other satellites. Break-up requires that the projectile kinetic energy should exceed the gravitational binding energy of the parent.

Table 1 **Physical and orbital properties of the irregular satellites***

| Name | Semi-major axis, *a* (km) | Inclination, *i* (degrees) | Eccentricity, *e* | Period (days) | Mag. ($m_{\mathrm{R}}$) | Diameter (km) | Year of discovery |
|---|---|---|---|---|---|---|---|
| Themisto Group | Prograde | | | | | | |
| XVIII Themisto | 7,507,000 | 43.08 | 0.24 | 130.0 | 21.0 | 8 | 2000 |
| Himalia Group | Prograde | | | | | | |
| XIII Leda | 11,165,000 | 27.46 | 0.16 | 240.9 | 19.2 | 20 | 1974 |
| VI Himalia | 11,461,000 | 27.50 | 0.16 | 250.6 | 14.2 | 170 | 1904 |
| X Lysithea | 11,717,000 | 28.30 | 0.11 | 259.2 | 17.9 | 36 | 1938 |
| VII Elara | 11,741,000 | 26.63 | 0.22 | 259.6 | 16.0 | 86 | 1905 |
| S/2000 J11 | 12,555,000 | 28.30 | 0.25 | 287.0 | 22.4 | 4 | 2000 |
| Ananke Group | Retrograde | | | | | | |
| S/2001 J10 | 19,302,000 | 145.8 | 0.14 | 550.7 | 23.1 | 2 | 2001 |
| S/2001 J7 | 21,027,000 | 148.9 | 0.23 | 620.0 | 22.8 | 3 | 2001 |
| XXII Harpalyke | 21,105,000 | 148.6 | 0.23 | 623.3 | 22.2 | 4 | 2000 |
| XXVII Praxidike | 21,147,000 | 149.0 | 0.23 | 625.3 | 21.2 | 7 | 2000 |
| S/2001 J9 | 21,168,000 | 146.0 | 0.28 | 623.0 | 23.1 | 2 | 2001 |
| S/2001 J3 | 21,252,000 | 150.7 | 0.21 | 631.9 | 22.1 | 4 | 2001 |
| XXIV Iocaste | 21,269,000 | 149.4 | 0.22 | 631.5 | 21.8 | 5 | 2000 |
| XII Ananke | 21,276,000 | 148.9 | 0.24 | 610.5 | 18.3 | 28 | 1951 |
| S/2001 J2 | 21,312,000 | 148.5 | 0.23 | 632.4 | 22.3 | 4 | 2001 |
| Carme Group | Retrograde | | | | | | |
| S/2001 J6 | 23,029,000 | 165.1 | 0.27 | 716.3 | 23.2 | 2 | 2001 |
| S/2002 J1 | 23,064,000 | 165.0 | 0.26 | 715.6 | 22.8 | 3 | 2002 |
| S/2001 J8 | 23,124,000 | 165.0 | 0.27 | 720.9 | 23.0 | 2 | 2001 |
| XXI Chaldene | 23,179,000 | 165.2 | 0.25 | 723.8 | 22.5 | 4 | 2000 |
| XXVI Isonoe | 23,217,000 | 165.2 | 0.25 | 725.5 | 22.5 | 4 | 2000 |
| XXV Erinome | 23,279,000 | 164.9 | 0.27 | 728.3 | 22.8 | 3 | 2000 |
| XX Taygete | 23,360,000 | 165.2 | 0.25 | 732.2 | 21.9 | 5 | 2000 |
| XI Carme | 23,404,000 | 164.9 | 0.25 | 702.3 | 17.1 | 46 | 1938 |
| S/2001 J11 | 23,547,000 | 165.2 | 0.26 | 741.0 | 22.7 | 3 | 2001 |
| XXIII Kalyke | 23,583,000 | 165.2 | 0.25 | 743.0 | 21.8 | 5 | 2000 |
| Pasiphae Group | Retrograde | | | | | | |
| S/2001 J4 | 23,219,000 | 150.4 | 0.28 | 720.8 | 22.7 | 3 | 2001 |
| VIII Pasiphae | 23,624,000 | 151.4 | 0.41 | 708.0 | 16.6 | 60 | 1908 |
| XIX Megaclite | 23,806,000 | 152.8 | 0.42 | 752.8 | 21.7 | 6 | 2000 |
| S/2001 J5 | 23,808,000 | 151.0 | 0.31 | 749.1 | 23.0 | 2 | 2001 |
| IX Sinope | 23,939,000 | 158.1 | 0.25 | 724.5 | 17.6 | 38 | 1914 |
| XVII Callirrhoe | 24,102,000 | 147.1 | 0.28 | 758.8 | 20.3 | 8 | 1999 |
| S/2001 J1 | 24,122,000 | 152.4 | 0.32 | 765.1 | 22.0 | 4 | 2001 |

*Orbital data are from R. Jacobson (http://ssd.jpl.nasa.gov/sat_elem.html); fits are over a 1,000-year time span. *a*, mean semi-major axis with respect to Jupiter; *i*, mean inclination of orbit with respect to Jupiter's equator; *e*, mean eccentricity; period, orbital period of satellite around Jupiter; mag., apparent red (0.65 μm wavelength) magnitude; diameter, diameter of satellite, assuming a geometric albedo of 0.04.

If half of the kinetic energy of the comet goes into breaking apart the target satellite[23] and if the collision velocity is about 5 km s$^{-1}$, a target satellite with $r = 25$ km must be struck by a $r \approx 1$ km projectile in order to be disrupted. At the present epoch, the flux of Jupiter-crossing comets of this size is $10^3$ to $10^4$ times too small to shatter the irregular satellite parent bodies[24]. However, lunar crater counts show a very rapid fall in the projectile flux in the first few 100 Myr, approaching the current steady state flux about $3.5 \times 10^9$ years ago[25]. The time-averaged flux of lunar impactors in the last $4.5 \times 10^9$ years is roughly $10^5$ times the current flux. If applicable at Jupiter, this large initial flux would be sufficient to shatter each of the parent satellites and could explain the observed groups. 'Particle-in-a-box' type calculations show that the timescales for collision among the known satellites are very long. For the retrograde satellites the timescale ($\sim 10^{11}$ years) is much larger than the age of the Solar System, while the progrades have a shorter, but still long, collision timescale ($\sim 10^9$ years). Thus, fragmentation by collision among the current satellites seems unlikely. However, it is possible that Jupiter once held a much larger population of irregular satellites and that the observed groups are merely the products of disruptive, post-capture collisions amongst them.

Although Jupiter currently possesses the largest number of known satellites of any of the planets, the other giant planets also have significant irregular satellite populations. All are thought to have been captured by their respective planets[6,8]. In common with Jupiter, the other systems show dynamical grouping, but the satellites of more distant planets are fainter and observationally less well characterized. If Jupiter were displaced to the distances of the other giant planets we would only be able to detect about 11 of the 32 known irregular satellites at Saturn's distance, six at Uranus's distance, and two at Neptune's distance in a survey of each Hill sphere to 24th magnitude (corresponding to radii of 3.5, 18, and 40 km, respectively). In fact, Saturn has 13 known irregulars within three or four distinct dynamical groups, Uranus has five with one or two distinct groups, and Neptune has two irregulars brighter than 24th magnitude. By this measure, the four giant planets possess about the same number of irregular satellites and satellite groups with no dependence on the planet's mass. This is especially remarkable given that the ice giants Uranus and Neptune may have had formation histories quite different from the gas giants Jupiter and Saturn[13,26].

*Note added in proof:* A number of new small irregular satellites were discovered after the submission of this paper (S.2003 J1 to J20; refs 7, 27). With the exception of S/2003 J20, the new satellites fall into the retrograde dynamical groupings described in this paper. The orbital elements of the new objects are still uncertain and therefore have not been fully incorporated into the paper. S/2003 J20 has a prograde orbit unlike any other known satellite ($a \approx 17{,}100{,}000$ km ($0.33\,R_{\mathrm{H}}$), $i \approx 55°$, $r \approx 1.5$ km). A few of the new discoveries may have inclinations and semi-major axes similar to Sinope. ☐

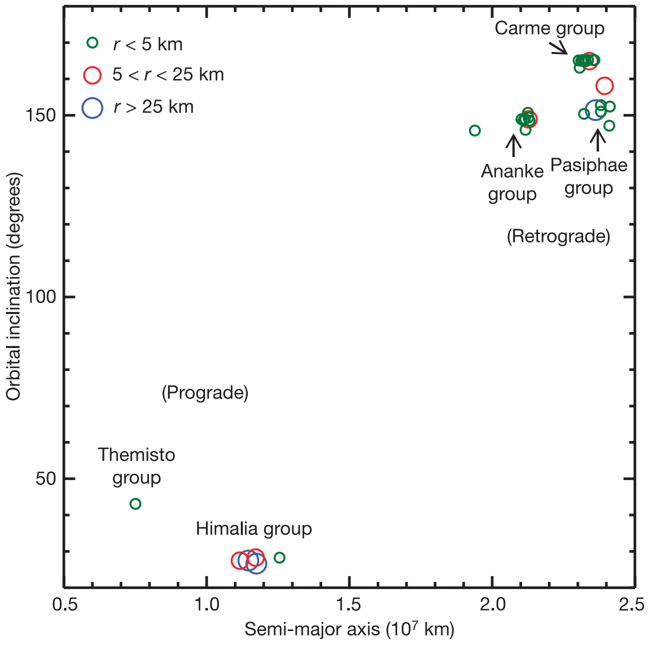

**Figure 2** The mean semi-major axes versus the mean inclinations of the irregular satellites of Jupiter. Five distinct clusters are evident with the Ananke, Pasiphae and Carme retrograde groups at about 300 Jupiter radii with mean inclinations around 149, 151 and 165 degrees respectively, the Himalia (main) prograde group at about 155 Jupiter radii with inclinations near 28 degrees, and the Themisto prograde group with Themisto as the lone member at about 100 Jupiter radii and inclination of 45 degrees. Satellite symbols are plotted according to size bins. S/2001 J10 is the retrograde satellite to the left of the Ananke group. Its orbit, along with Sinope's and Pasiphae's, may have been modified through resonances (R. Jacobson, personal communication; ref. 28). The satellites discovered in 2000 and 2001 have been observed for at least two oppositions, except for S/2000 J11 which has only about a month of observations.

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