M. ASBURY

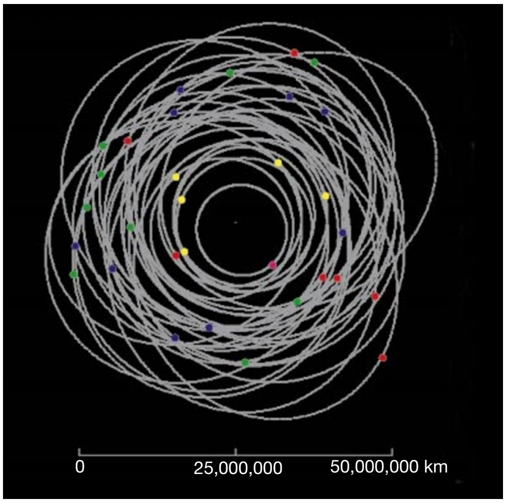

Figure 2 **The orbits of Jupiter's outer satellites. The giant planet is at the centre of the image (taken from an animation program[13]), with 31 of its distant satellites grouped into the families identified by Sheppard and Jewitt[1]. Prograde objects (pink and yellow) circle Jupiter in the anticlockwise direction when viewed from above Jupiter's north pole, while the three retrograde families (blue, green and red) circle clockwise. The few known prograde orbits nestle inside the far more numerous retrograde ones.**

and its largest moon, haze-enshrouded Titan, were first seen by Christiaan Huygens about 50 years later, and, in 1684, the discoveries of icy Dione and Tethys established Saturn as the planet with the most moons, a title it held for 230 years. Jupiter's Sinope, spotted in 1914, evened the score at nine known moons apiece, and two additional findings in 1938 allowed the giant planet to surge into the lead. Saturn staged a surprise comeback in 1980, when seven new satellites were spotted by the Voyager spacecraft and ground-based observers. Then came the great upset of 1999: dark horse Uranus revealed three additional outer satellites[2] and vaulted to the forefront. But the title has since been reclaimed — first by Saturn, with a dozen new discoveries reported[3] in 2000, and now by Jupiter, with the 23 findings detailed in this issue[1].

Currently, the number of known planetary moons stands[4] at 128 (Fig. 1). More than half of this total has been added since 1997, when Brett Gladman and colleagues found the first two distant, or 'irregular', satellites of Uranus[5]. The large number of satellite discoveries over the past six years, at an ever quickening pace, is reminiscent of the situation following Jewitt and Luu's 1992 discovery[6] of the first trans-neptunian (or Kuiper belt) objects. Both population explosions have been fuelled by major improvements in digital-camera technology[7].

Nearly two-thirds of the known moons (including all of the recent discoveries) are irregular satellites, orbiting far from their planets along highly tilted, elliptical paths. These objects are believed to have been captured by their planets from independent orbits around the Sun early in the history of the Solar System. Regular satellites, by contrast, have much smaller, untilted, circular orbits, and were probably formed out of the disks of gas and dust that surrounded the giant planets in their youth. Energy dissipation in these early accretion disks also acted to facilitate the capture of the irregular satellites[8].

The orbital distributions of irregular satellites at Jupiter (Fig. 2) and Saturn, particularly their tilt angles, show several intriguing patterns that hint at past dynamical and collisional processes. No moons have yet been found on orbits tipped by more than about 55° to the planet's orbital plane. This is due to gravitational forcing from so-called solar tides, which is the largest perturber of distant planetary satellites[9–11]. Objects with greater tilts experience large, correlated changes in their inclinations and eccentricities which put them on orbits that penetrate deep into the inner jovian system. Such objects are lost as a result of destabilizing gravitational kicks from large regular satellites and, in some cases, through direct collisions[11].

The lack of highly tilted orbits means that the orbits may be cleanly divided into prograde (those that circulate in the same direction as the planet's motion around the Sun), and retrograde (those that move in the opposite direction). At Saturn and Neptune, the number of distant, prograde moons is comparable to the number of retrograde objects, but at Jupiter and Uranus, the retrogrades dominate. Also in this issue (page 264), Astakhov and colleagues[12] proffer an explanation for the striking Jupiter–Saturn dichotomy. Through numerical integrations of the capture process, they find that interactions with Jupiter's large regular satellite Callisto preferentially remove moons with prograde orbits, which penetrate closer to Jupiter than retrogrades (see, for example, ref. 10). Titan, closer to Saturn than Callisto is to Jupiter, is less efficient at removing the prograde population. Although alternative explanations for the dichotomy cannot be ruled out, the orbital properties of the extant satellites certainly put important constraints on conditions that existed during the capture process[12].

The prograde and retrograde groups can be further divided into families of objects that share similar characteristics, such as the size, shape and tilt of their orbits. At least five such families are evident[1,11] at Jupiter and four are seen[3] at Saturn. Like asteroid families, each satellite family appears to have been formed from the collisional breakup of a larger object[1,3,11].

So satellites are occasionally shattered by breakups, but do moons ever merge? Although retrograde satellites at Jupiter now vastly outnumber the prograde irregulars, the latter (primarily Himalia) account for nearly 98% of the mass of the distant jovian satellites. And at Saturn, despite similar numbers of prograde and retrograde irregulars, retrograde Phoebe dominates with approximately 99.5% of the orbiting mass. Perhaps Himalia and Phoebe are merely the largest surviving members of much bigger primordial populations. Alternatively, these two large satellites may have grown significantly by cannibalizing some of their smaller neighbours, or by accreting inwardly migrating solids in the latter stages of giant-planet growth. This hypothesis is supported by the fact that both Phoebe and Himalia lie near the inner edge of the zone of irregular satellites (where collisional accumulation rates are fastest) and have relatively low orbital eccentricities and tilts. These and other satellite evolutionary processes need to be explored more fully.

Although ever smaller moons around the giant planets will undoubtedly be discovered, it is likely that Jupiter, whose satellites appear brightest because of their proximity to the Earth and the Sun, will continue to dominate the moon count for the foreseeable future. ■

Douglas P. Hamilton is in the Department of Astronomy, University of Maryland, College Park, Maryland 20742, USA.
e-mail: hamilton@astro.umd.edu

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Corrections

● In the News and Views in Brief item "Cell biology: Muscle mice" (*Nature* **422,** 393; 2003), the adult stem cells referred to were derived not from human bone marrow but from synovial membrane.

● The correctly spelt name of the author whose work was discussed by Ian Stewart in "Mathematics: Regime change in meteorology" (*Nature* **422,** 571–573; 2003) is Daan Crommelin.