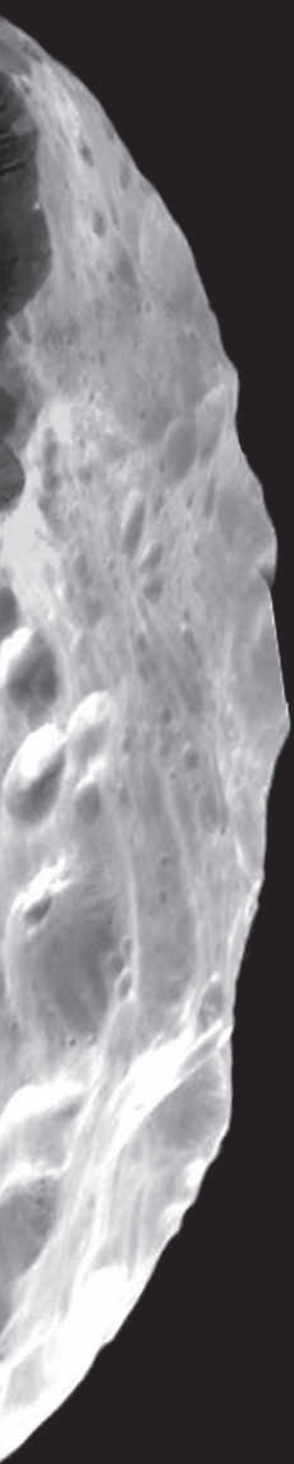
GUNKED-UP, ICY BODY, Saturn's largest irregular moon, Phoebe, looks like a comet that was plucked from solar orbit. The craters are named after the Argonauts of Greek mythology: the largest, at top, is Jason; immediately to its left is Erginus; and the one in shadow along the bottom rim is Oileus.



DON DIXON; NASA/JPL/SSI

The STRANGEST Satellites in the Solar System

Found in stretched, slanted, loop-d-loop orbits, an odd breed of planetary satellites opens a window into the formation of the planets

By David Jewitt, Scott S. Sheppard and Jan Kleyna

FIVE YEARS AGO TWO OF US WHILED AWAY A CLOUDY NIGHT ON THE SUMMIT OF MAUNA KEA IN HAWAII by placing bets on how many moons remained to be discovered in the solar system. Jewitt wagered $100 that a dedicated telescopic search could find, at most, 10 new ones. After all, he reasoned, in the entire 20th century, astronomers had come across only a few. Sheppard more optimistically predicted twice as many, given the increased sensitivity of modern astronomical facilities.

Sheppard is now a richer man. Since that night, our team has discovered 62 moons around the giant planets, with more in the pipeline. Other groups have found an additional 24. (In strict astronomical parlance, they are "satellites," not "moons." There is only one moon and it is Earth's satellite. But even astronomers generally adopt the popular usage.) No one predicted that the family of the sun had so many members lurking in the shadows. They are classified as "irregular," meaning that their orbits are large, highly elliptical and tilted with respect to the equators of their host planets. So-called regular moons, such as Earth's or the large Galilean satellites of Jupiter, have comparatively tight, circular and nearly equatorial orbits.

Odder still, most of the irregulars have retrograde orbits, which means they each trundle around their host planet in a direction opposite to the sense of the rotation of the planet. In contrast, regular moons have prograde orbits. For example, as seen from a position above Earth's North Pole, our moon travels counterclockwise—the same direction in which Earth rotates on its axis and revolves around the sun. The other planets also move counterclockwise, a pattern that presumably reflects the swirling of the disk of gas and dust out of which they emerged four and a half billion years ago. Regular moons share this motion because, astronomers think, they coalesced from disks around their respective planets. So the contrary behavior of the irregular moons is a sign of a different origin.

These bodies are not well explained by standard models, and a wave of fresh theoretical work is under way. It seems that they are products of a long-gone epoch when the gravitational tug of the newly formed planets scattered—or snatched—small bodies from their original orbits. Studying them promises to illuminate the early stages in the development of the solar system.

Black Sheep

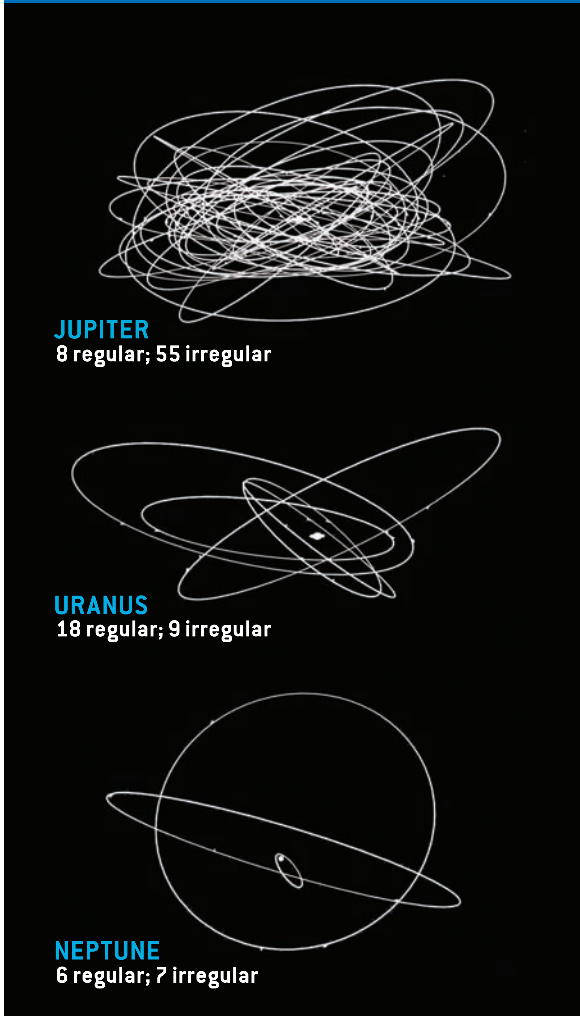
ALTHOUGH THE FIRST known irregular moon, Neptune's Triton, was discovered in 1846, most escaped detection until recently because they tend to be smaller and thus fainter than their regular counterparts. Adding to the challenge, they are distributed over a much larger region of space. For instance, Jupiter's outermost regular satellite, Callisto, orbits 1.9 million kilometers from the planet, whereas its known irregular moons range as far away as 30 million kilometers. That distance is comparable to the size of Jupiter's gravitational realm, or Hill sphere, beyond which the sun would pry loose any moon. If visible to the eye, Jupiter's Hill sphere would appear 10 degrees across—20 times the angular diameter of the full moon. It is huge compared with the fields of view of most telescopes.

Scanning such a vast area for moons demands the newest, largest digital detectors and the analysis of up to 100 gigabytes of data a night [*see box on page 46*]. Our own Hawaii Moon Survey focused initially on Jupiter, whose proximity allows us to probe small moons that would be too faint to detect around the other, more distant giant planets. Teams led by Brett Gladman of the University of British Columbia, Matthew Holman of the Harvard-Smithsonian Center for Astrophysics (CfA) and J. J. Kavelaars of the National Research Council of Canada's Herzberg Institute of Astrophysics have mounted parallel efforts to survey Saturn, Uranus and Neptune.

All four giant planets, irrespective of mass, turn out to have similar irregular moon systems. Extrapolating from the findings so far, we estimate that each has about 100 irregular moons larger than one kilometer in diameter. The bodies occupy a wide range of sizes, with smaller ones being much more abundant. In Jupiter's case, the size range extends from the largest irregular, J6 Himalia, at about 180 kilometers in diameter, down to the smallest objects at only one or two kilometers across.

The orbits of these moons are some of the most complicated in the solar system. Because they roam so far from their host planet, they are tugged by both planetary and solar gravity, and their orbits precess rapidly—that is, the long axis of the ellipse representing the orbit rotates.

A SWARM OF MOONS



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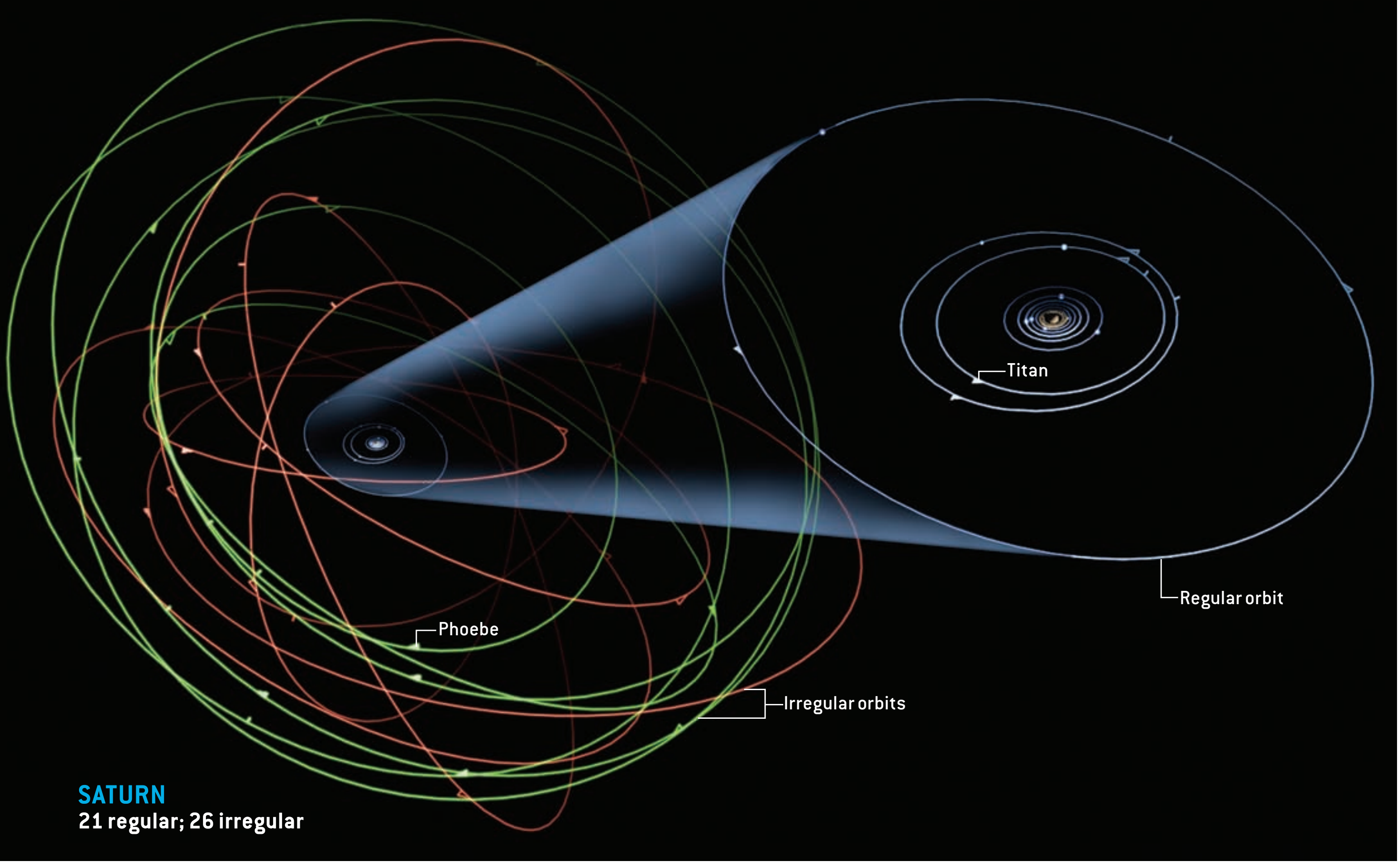
Overview/*Irregular Moons*

- Astronomers used to think that most planetary moons formed from disks around their respective planets—reproducing, in miniature, the formation of the solar system itself. These moons orbit in the same plane as the planet's equator and in the same direction as the planet's spin. The few bodies not fitting this pattern were deemed "irregular."
- A recent flood of discoveries using advanced digital detectors shows that irregular moons are actually the majority. Their long, looping, slanted orbits indicate that they did not form in situ but instead in paths encircling the sun. In essence, they are asteroids or comets that the planets somehow captured.
- Neither the source region nor the mechanism of capture is well understood. The moons might have come from the Kuiper belt beyond Neptune or from regions closer in. Their capture may have involved collisions or other interactions in a younger, more densely populated solar system.

The full extent of the system of moons around Saturn was barely known until recent years. The satellites fall into two broad categories: regular moons (*blue*), such as Titan and Iapetus, have tight, nearly coplanar orbits; irregular moons, such as Phoebe, have wider, variously oriented orbits. Some revolve in the same direction as Saturn rotates (*red*); others go the opposite way (*green*). Similar systems surround the other giant planets (*far left*). These diagrams show a sampling of the total number of moons.



SATURN
21 regular; 26 irregular

The rotation is so rapid that it is not even accurate to represent the paths as closed loops. Instead the moons trace out strange, looping trajectories akin to figures from the children's toy Spirograph.

Cosmic Polyrhythm

WHEN THE VARIOUS influences on the moons act in synchrony, the situation gets especially complex. For instance, if the rate of precession matches the rate at which the host planet orbits the sun, the moon is said to be in an "evection" resonance. The otherwise modest effects of solar gravity accumulate over time, destabilizing the orbit; the ellipse elongates to such an extent that the moon either collides with the planet (or one of its larger moons) or breaks out of the Hill sphere and falls into the gravitational clutches of the sun. Prograde orbits are more vulnerable than retrograde ones. If irregular moons were originally equally likely to be either prograde or retrograde, this resonance could explain why most moons are now retrograde.

Another resonance, known as the Kozai resonance, couples the tilt and shape of the orbit. Moons that are hauled into inclined orbits wind up on highly stretched ellipses, again leading potentially to their ejection or destruction. That may be why observers have found no moons with inclinations between 50 and 130 degrees. In short, the irregular moons we see today appear to be the survivors of gravitational interactions that cleared out many of their brethren.

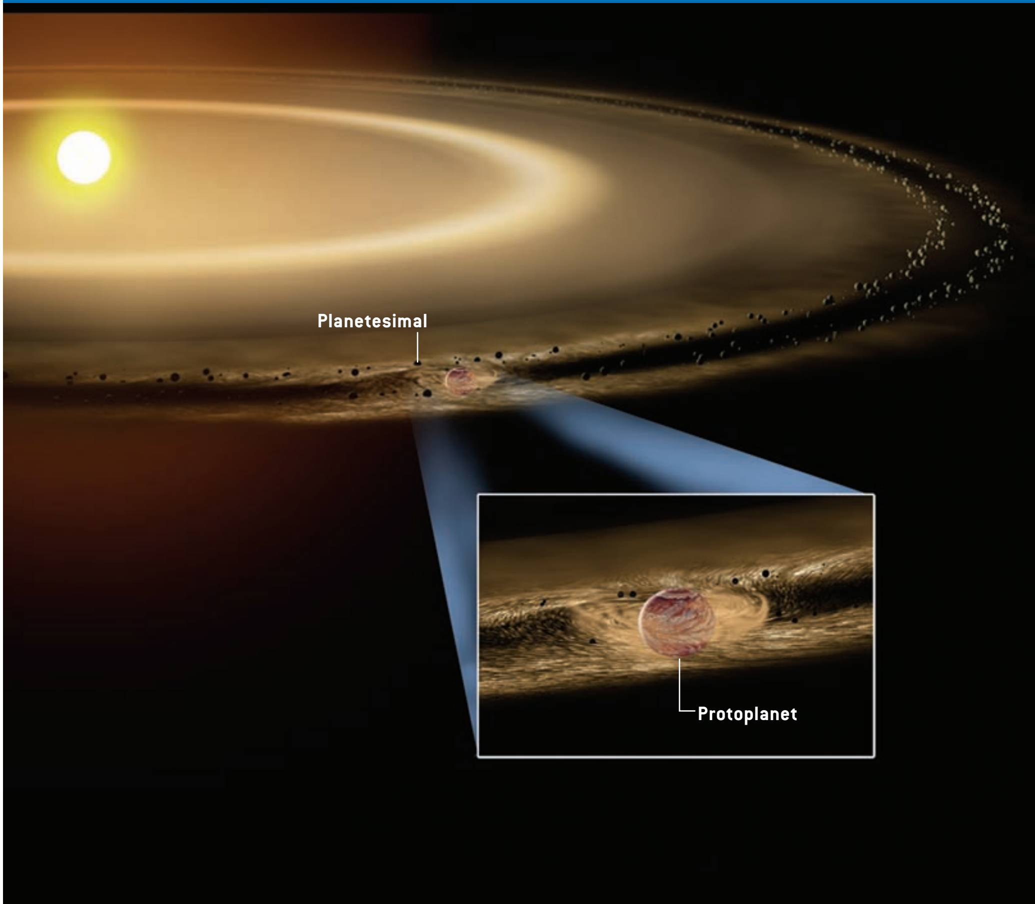
Still other features of the orbits require processes beyond those of gravity. The moons belong to distinct groups, or families, having similar orbits. Jupiter's groups, for instance, have up to 17 members each. The most straightforward interpretation is that the members of a group are pieces of a larger moon that was shattered by an impact and continue to follow in that body's orbit. If so, many of the irregular moons we see today are the second generation—one step removed from the original population.

David Nesvorny of the Southwest Research Institute in Boulder, Colo., and his collaborators have modeled the collisional disruption of moons in detail. They find that in the present day it is rare for a moon to collide with another moon or with an interplanetary body such as a comet. Therefore, the existence of groups hints at an earlier time when the populations of irregular moons or comets (or both) were much larger than now and collisions were much more frequent.

Beyond learning something about the orbits of irregular moons, astronomers have made some progress in discerning other properties. Most of the moons are so faint that they have been able to uncover very little about their composition. Tommy Grav of CfA and Terry Rettig of the University of Notre Dame have found, however, that moons within a group tend to have similar colors. Color is a proxy for composition, so this discovery implies a likeness in makeup—further supporting the idea that group members are fragments of a larger, bygone parent body.

One of the few irregular moons that astronomers know in any detail is Saturn's Phoebe, which NASA's Cassini spacecraft visited in June 2004. Cassini obtained very high resolution images, which showed a high density of craters on Phoebe's surface, and also recorded the spectra of reflected sunlight, which revealed water and carbon dioxide ices. The two irregular moons of Neptune seen by the Voyager 2 space probe, Nereid and Triton, also have icy surfaces. The ices hint that these objects formed relatively far from the sun, like comets. The irregular moons of Jupiter are pitch-black and appear to be devoid of ice, probably because they are closer to the sun and too warm for ice to be stable. In this sense, Jupiter's irregular moons closely resemble comets that have lost their volatile compounds.

HOW TO SNAG A MOON



The strange orbital properties of the irregular moons indicate that they started off in orbit around the sun and later were captured by their current host planets. Astronomers have proposed three capture mechanisms.

For all three, the initial stage is the formation of asteroid-size bodies called planetesimals. Many agglomerate to form the rocky cores of the giant planets. The leftovers are vulnerable to being captured.

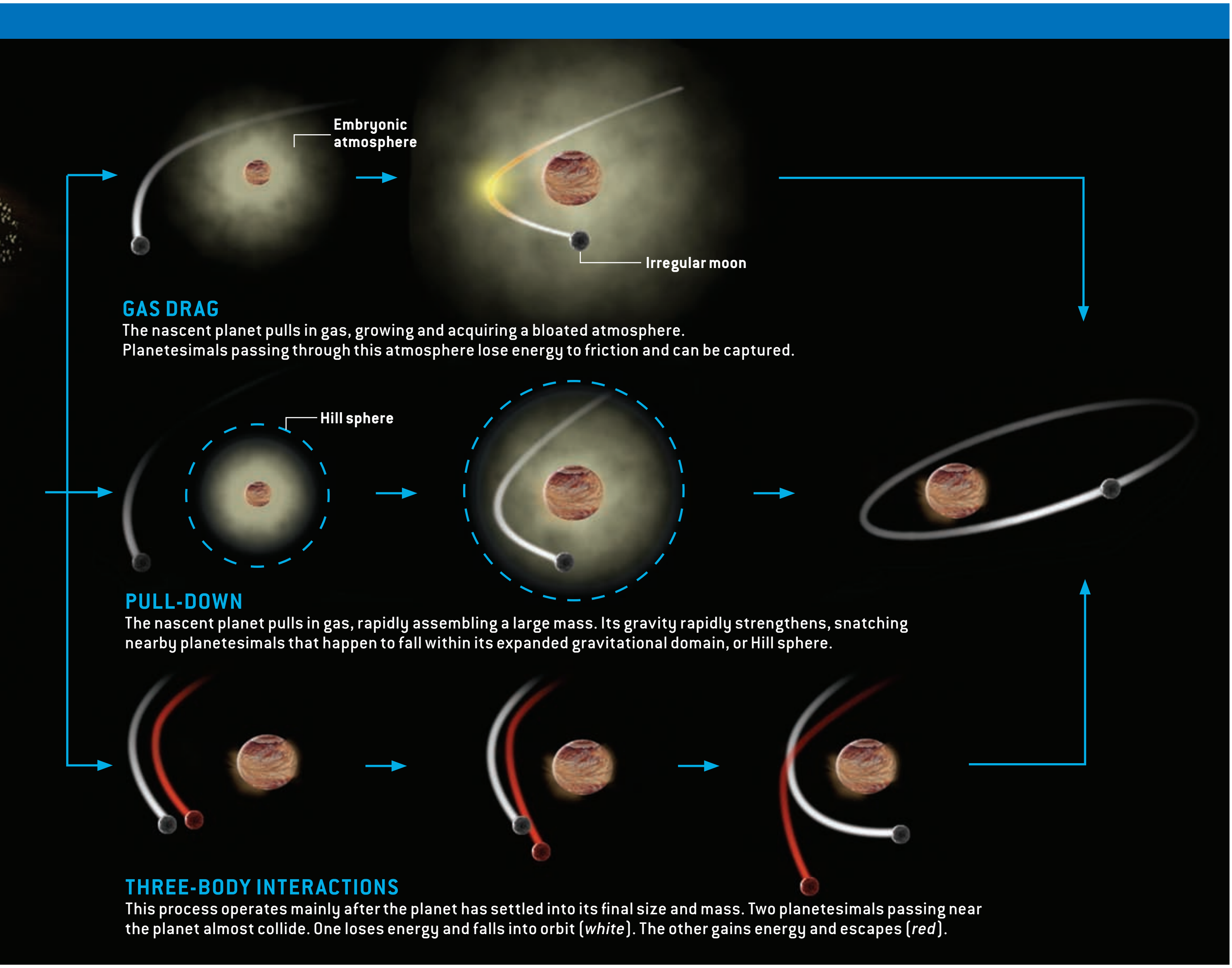
What a Drag

THE PROPERTIES of the irregular moons—especially their retrograde orbits—suggest that they did not form in situ. Instead they must be leftover planetary building blocks, like asteroids or comets, that originally orbited the sun and were somehow captured by the planets. Understanding how that happened is not easy. In the complex interplay of solar and planetary gravity, asteroids and comets are routinely pulled into short-lived orbits around the giant planets. Temporary capture is analogous to the trapping of leaves in a vortex on a windy autumn day. The leaves enter the vortex, swirl around for perhaps a few dozen times and then are blown out in an unpredictable way.

Examples of this type of capture include the well-known comet D/Shoemaker-Levy 9 (the "D" stands for "defunct"), which entered a temporary orbit around Jupiter sometime in the 20th century and rammed into the planet in 1994. Had it not met an untimely death, the comet would have been ejected back into heliocentric orbit within a few hundred years. Astronomers know of several objects that survived temporary capture by Jupiter and returned to orbiting the sun.

THE AUTHORS

DAVID JEWITT, SCOTT S. SHEPPARD and *JAN KLEYNA* are the world's most prolific discoverers of planetary moons. Jewitt traces his interest in astronomy to age seven, when he was astonished by a spectacular meteor shower visible against the sodium-lit night skies of industrial north London. He is now a professor at the University of Hawaii and a member of the National Academy of Sciences. Sheppard, his former graduate student, recently became a Hubble postdoctoral fellow in the department of terrestrial magnetism at the Carnegie Institution of Washington. Kleyna grew up on a farm in Maine, enjoys incomprehensible art-house cinema and is now a Parrent postdoctoral fellow at the University of Hawaii, where he mainly studies dark matter in dwarf galaxies.



GAS DRAG
The nascent planet pulls in gas, growing and acquiring a bloated atmosphere. Planetesimals passing through this atmosphere lose energy to friction and can be captured.

PULL-DOWN
The nascent planet pulls in gas, rapidly assembling a large mass. Its gravity rapidly strengthens, snatching nearby planetesimals that happen to fall within its expanded gravitational domain, or Hill sphere.

THREE-BODY INTERACTIONS
This process operates mainly after the planet has settled into its final size and mass. Two planetesimals passing near the planet almost collide. One loses energy and falls into orbit (*white*). The other gains energy and escapes (*red*).

DON DIXON

But for a body to be permanently captured from heliocentric orbit into a bound, stable orbit around a planet, it must lose some of its initial energy. Essentially the body has to be slowed down to prevent it from escaping again. No efficient process of energy dissipation operates in the solar system today. Moon capture, then, must have occurred long ago, at a time when the solar system had different properties. In the 1970s theorists proposed three possible mechanisms, all functioning during or soon after the epoch of planet formation.

The first, advanced by James B. Pollack and Joseph A. Burns, then at the NASA Ames Research Center, and Michael E. Tauber of Cornell University, argues that the moons lost energy to friction generated as they passed through the vastly extended atmospheres of the embryonic gas giant planets. Jupiter and Saturn, quite unlike Earth and other terrestrial planets, are composed primarily of hydrogen and helium. Most probably, they formed when a core of rock and ice, of roughly 10 Earth-masses, pulled in vast quantities of gas from the primordial disk surrounding the young sun. Before settling into their modern, relatively compact forms, the planets may have passed through a transient, distended phase, during which their atmospheres extended hundreds of times farther than they do now.

In true Goldilocks style, a passing asteroid or comet would have met one of three distinct fates, depending on its size. If it was too small, it burned up in the bloated atmosphere, like a meteor. If it was too large, it plowed through unimpeded and continued in orbit about the sun. If it was just right, it slowed down and was captured. This process is a natural version of the aerobraking procedure that many planetary probes have used to enter orbit.

One problem with the gas-drag model is that it does not explain the presence of irregular satellites around Uranus and Neptune. Those planets are not gas giants but rather ice giants—dominated by rock and ice, with rela-

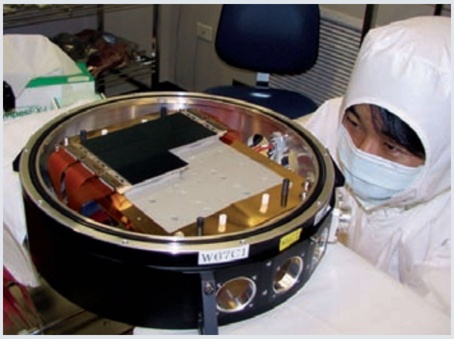
Watchers of the Skies

Far-flung, tiny, dimly lit: irregular moons are among the most challenging observational targets in the solar system. Finding them requires the world's most powerful survey telescopes—that is, instruments that scan broad swaths of the sky rather than concentrating on single, limited areas. Our team made most of our discoveries using the Canada-France-Hawaii Telescope and Subaru Telescope on Mauna Kea in Hawaii. They are equipped with digital detectors of more than 100 million pixels each.

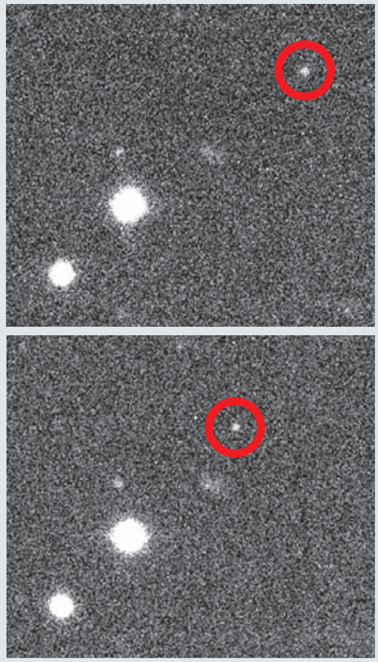
The central problem is to distinguish objects in the solar system from more distant stars and galaxies. Observers use two methods. The first involves a distance measurement. We compare three images of the same area, spaced some time apart. During that time, Earth moves partway around the sun, changing our vantage point and causing bodies to appear to shift position; the closer the body, the more it appears to move.

The second method involves a velocity measurement. We take tens of images of one field, offset them depending on the expected orbital speed of the irregular moons we are looking for, and add them together. In the summed image, background stars appear as streaks and the irregular moons as bright dots. Because this method uses more images of a given area of sky, it is more sensitive to faint objects than the first approach but takes longer to perform a full survey. To make sure the bodies are moons rather than asteroids or comets, we monitor them for several months and work with Brian Marsden of the CfA to check whether they orbit their respective planets.

—D.J., S.S.S. and J.K.



FOR SURVEYING large areas of the sky, one of the best detectors is the Subaru Prime Focus Camera, a mosaic of 10 eight-megapixel CCD chips.



MOVING PINPRICK OF LIGHT: Jupiter's satellite S/2003 J14 was discovered on February 26, 2003, in these two images taken 39 minutes apart. The other objects here are background stars. Thought to be about two kilometers across, the moon has an orbit that stretches 31 million kilometers away from the giant planet.

tively modest veneers of hydrogen and helium. Because of their greater distance from the sun and the consequently lower density of material in the outer regions of the circumsolar disk, their cores took a longer time to reach the critical mass needed to precipitate gaseous collapse. Before that happened, the solar nebula had largely dissipated, and so Uranus and Neptune never had extended atmospheres, like those of Jupiter and Saturn. How can gas drag operate when there is not much gas?

Three's a Crowd

THE SECOND METHOD also places capture during the planetary growth phase. The accretion of gas onto the cores of the gas giants would have caused their mass to shoot upward in a self-reinforcing process, leading to sudden growth in the size of the Hill sphere around each planet. Asteroids and other objects that were unlucky enough to be nearby at the moment of this runaway growth would have found themselves trapped by the abruptly extended reach of the planets' gravity. This mechanism of capture was first expounded by Thomas A. Heppenheimer and Carolyn Porco, both then at the California Institute of Technology. They called it, somewhat confusingly, "pull-down" capture.

Like gas drag, however, this mechanism has trouble accounting for the moons around Uranus and Neptune, neither of which underwent a runaway growth in mass. Most models indicate that these planets grew slowly by accumulating asteroid- and comet-size bodies, perhaps taking tens or hundreds of millions of years to reach their present-day masses. Even Jupiter and Saturn would have had to grow within a matter of millennia to make pull-down capture work, and many modelers are uncomfortable with such a short growth timescale. An alternative model for forming Uranus and Neptune, proposed by Alan Boss of the Carnegie Institution of Washington, is that they started out as massive as Jupiter and Saturn and were whittled down by ionizing radiation from nearby massive stars. The irregular moons are even harder to understand in this model, because a shrinking planet would tend to lose moons rather than grabbing them.

In both the gas-drag and pull-down models, the irregular moons were acquired early in solar system history, probably before Earth had reached a recognizable state. A third and very different scenario was proposed in 1971 by Bepi Colombo and Fred Franklin, both then at CfA. They suggested that collisions between two bodies in the Hill sphere of a planet could dissipate enough energy to allow one of them to be captured. This idea, called three-body capture, received relatively little attention in the 35 intervening years, perhaps because such collisions are exceedingly rare now.

Yet newer work shows that no collision is needed. The three bodies need only interact gravitationally. If they exchange energy, one can gain energy at the expense of the others. The process is a scaled-up version of the gravitational slingshot effect that space mission planners use to boost deep space probes. This past May, Craig Agnor of the University of California, Santa Cruz, and Doug Hamilton of the University of Maryland suggested another form of three-body capture in which a binary object is sheared apart by the gravity of a planet, leading one component to be ejected and the other pulled into orbit.

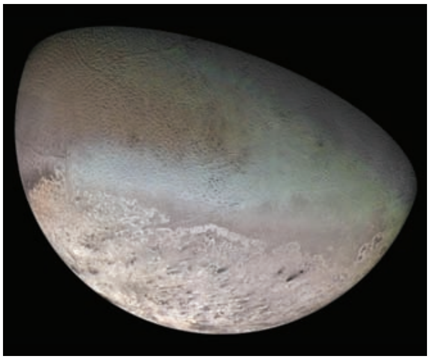
Planetary Movements

THREE-BODY CAPTURE is appealing in light of the new finding that all four giant planets have retinues of irregular moons. The process works for both gas giants and ice giants. It does not require a massive gaseous envelope or runaway planetary growth; all it needs is a sufficient number of collisions or near misses occurring close to the planets. These types of interactions would have been most probable near the end of the planet formation epoch, after the Hill spheres had grown to their present proportions but before the leftover debris of planet formation had been cleared out. Three-body capture might be able to account for why each planet has roughly the same number of irregular moons: although Uranus and Neptune are less massive than Jupiter and Saturn, they are farther from the sun, so their Hill spheres are comparable in size.

Even if three-body interactions explain how the irregular moons were captured, where did they come from to begin with? Researchers have suggested two distinct possibilities. The moons could be asteroids and comets that had agglomerated in the same general region of the solar system as the planet that eventually snatched them. Most of their cohorts were incorporated into the bodies of the planets or catapulted out of the solar system. The irregular moons were the lucky ones, neither eaten nor consigned to wander in the rarefied space between the stars.

Another possibility emerges from a recent model in which the solar system remained choked with debris until some 700 million years after the planets formed. Strong gravitational interactions between Jupiter and Saturn then set up oscillations that shook the entire system. Billions of asteroids and comets were scattered as the major planets lurched into their present, more stable orbits. A tiny fraction of the scattered bodies could have been captured. In this scenario, proposed last year by K. Tsiganis and his colleagues of the Observatory of Côte d'Azur, most of the bodies shaken loose originally formed beyond Neptune in the Kuiper belt [see "The Kuiper Belt," by Jane X. Luu and David C. Jewitt; SCIENTIFIC AMERICAN, May 1996].

Spectral measurements should one day be able to test these two hypotheses. If the irregular moons of different planets have different compositions, it would support the first hypothesis, in which moons formed near their eventual host planets. If they have similar compositions, that would argue for the second hypothesis, in which the moons all formed together and then dispersed. Thus, the moons could reveal whether the solar system went through a turbulent rearrangement.



NASA/JPL

LARGEST IRREGULAR MOON, Neptune's Triton, has baffled scientists since its discovery in 1846. Recent work suggests that it and a partner orbited the sun in mutual embrace, until Neptune sundered them and claimed Triton as its own.

Exploration of the irregular moon systems is ongoing. Two things are already evident: First, the capture of these moons must have occurred early in the solar system's history, either in association with planet formation or with its immediate aftermath. The modern solar system simply offers no suitable mechanism through which moons could be captured. Second, the similarities among the irregular moon populations of all four outer planets suggest that they arose by three-body interactions, the only known mechanism that is about as effective for Neptune as it is for Jupiter.

Like skid marks on a road after a car crash, the irregular moons swooping around the giant planets provide us with tantalizing clues about past events that we could never have witnessed directly. SA

MORE TO EXPLORE

The Discovery of Faint Irregular Satellites of Uranus. J. J. Kavelaars et al. in *Icarus,* Vol. 169, No. 2, pages 474–481; June 2004.

Discovery of Five Irregular Moons of Neptune. Matthew J. Holman et al. in *Nature,* Vol. 430, pages 865–867; August 19, 2004.

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Cassini Imaging Science: Initial Results on Phoebe and Iapetus. C. C. Porco et al. in *Science,* Vol. 307, pages 1237–1242; February 25, 2005.

Neptune's Capture of Its Moon Triton in a Binary-Planet Gravitational Encounter. Craig B. Agnor and Douglas P. Hamilton in *Nature,* Vol. 441, pages 192–194; May 11, 2006.

Hawaii Irregular Satellite Survey Web site: **www.ifa.hawaii.edu/~jewitt/irregulars.html**