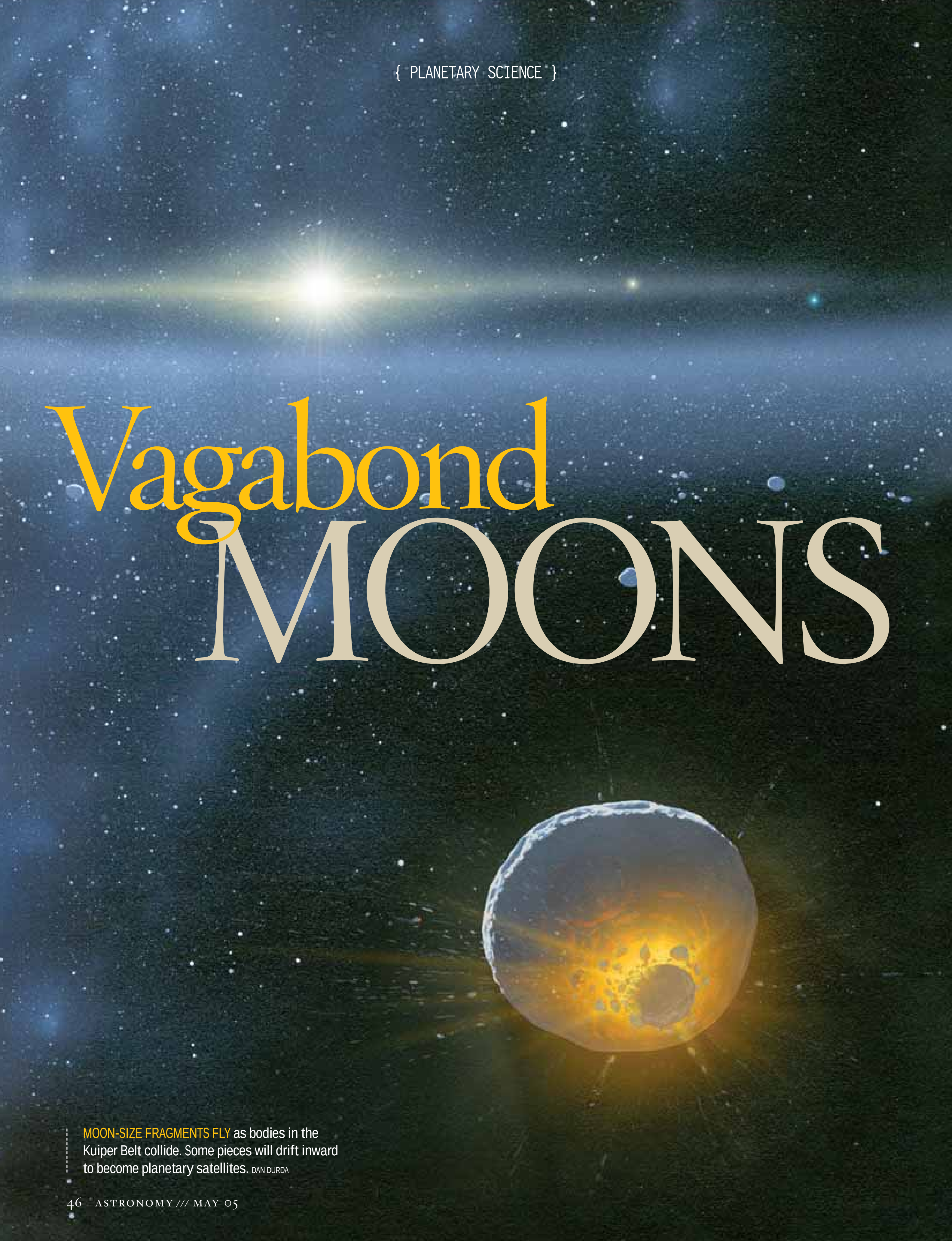
Vagabond MOONS



MOON-SIZE FRAGMENTS FLY as bodies in the Kuiper Belt collide. Some pieces will drift inward to become planetary satellites. DAN DURDA

Around each gas-giant planet orbit dozens of small moons born elsewhere. These far-ranging bodies are beginning to give scientists clues to the dark corners of the solar system. /// BY DAN DURDA AND DOUG HAMILTON

Late on a rainy Saturday evening in early October 1997, Brett Gladman carefully searched the star-filled CCD images he had recently helped a team of planetary scientists collect. The star fields surrounded the planet Uranus, and Gladman's elusive quarry were new uranian moons, small objects orbiting far from their giant blue-green parent and bound only weakly to it.

Other astronomers had sought new moons in the environs of the gas-giant planets before, but their searches had been sporadic and new discoveries were few. This time, however, Gladman spotted almost immediately two faint dots moving relative to the background stars at nearly the same rate as Uranus. Subsequent observations confirmed the objects, now named Sycorax and Caliban, were indeed new moons of Uranus.

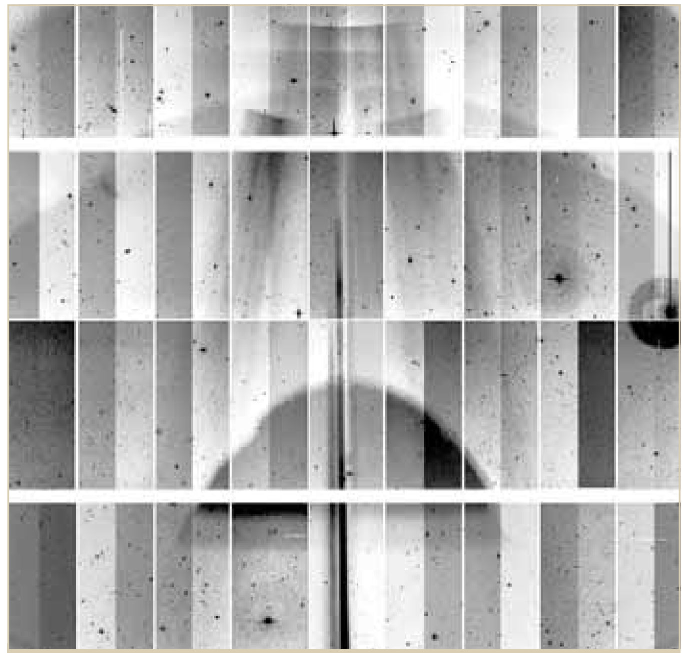
His discoveries were the first irregular satellites found using a ground-based telescope in nearly a quarter-century. (Irregular moons are those having large, highly eccentric, and often highly inclined, orbits.)

The discoveries came from an astronomical fishing expedition. A team of astronomers including Gladman, Phil Nicholson, and Joe Burns, all then at Cornell University, were observing with the 200-inch (5-meter) telescope on Palomar Mountain in California. They were hunting objects in the Kuiper Belt, a band of small, icy bodies extending outward from Neptune's orbit, 30 times farther from the Sun than Earth.

The 200-inch Hale telescope, completed in 1948, was once the world's largest, but numerous 8- and 10-meter telescopes have long since eclipsed it. The venerable instrument, however, still had some surprises in store.

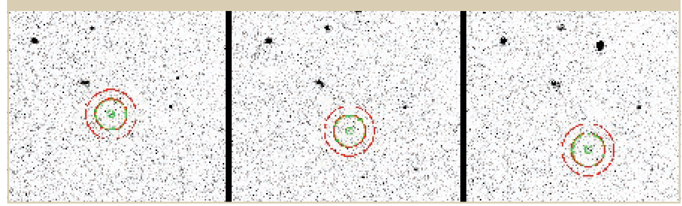
The first hour of the night was unusable for the astronomers' Kuiper Belt program because the star-crowded Milky Way was passing overhead. So the team focused its attention, and the telescope, on two handy targets: Uranus and Neptune. Nicholson reasoned that even though they could search only a small region around each planet, Palomar's modern CCD camera would capture objects 3 to 4 magnitudes fainter than the previous best attempts.

Those were the images in which Gladman spotted Caliban and Sycorax. His initial excitement, however, was tempered with a fair amount of skepticism when he told his collaborators about the result — not all



BRETT GLADMAN, UNIVERSITY OF BRITISH COLUMBIA

MOON-FINDING, PART 1. Searching for faint moons around bright planets resembles hunting fireflies near a bright lamp. In this mosaic of 72 seach frames (above), Jupiter lies outside the field of view at bottom. Somewhere within these images lurks jovian moon S/2003 J21, circled in the three discovery frames below.



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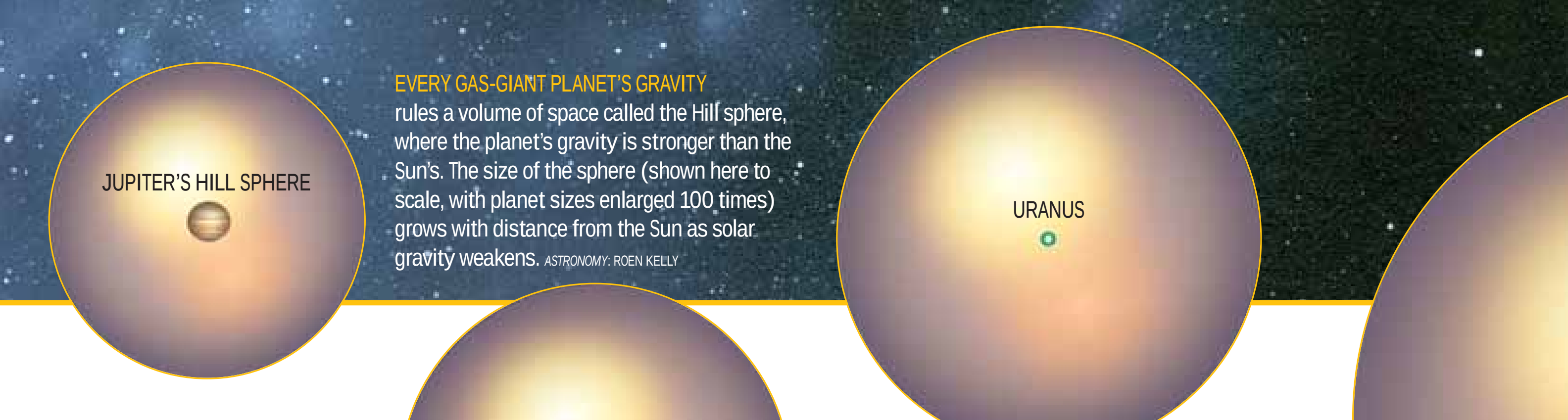
MOON-FINDING, PART 2. Discovering moons means sifting through dozens of long-exposure images looking for tiny specks of light moving in just the right way. Here, moon-finder Brett Gladman (left) confers with codiscoverer Lynne Allen.



EVERY GAS-GIANT PLANET'S GRAVITY rules a volume of space called the Hill sphere, where the planet's gravity is stronger than the Sun's. The size of the sphere (shown here to scale, with planet sizes enlarged 100 times) grows with distance from the Sun as solar gravity weakens. *ASTRONOMY:* ROEN KELLY

discoveries prove out in the end. However, the objects' motion in the images, plus calculations by Nicholson and Brian Marsden of the International Astronomical Union's Minor Planet Center, paid off when the team returned to the telescope later that month.

The two new moons were right where expected, slowly swooping around the distant planet. The discovery of two new uranian moons sparked a flurry of satellite hunts and finds over the next 6 years. By now, these have pushed the number of known moons in the solar system to 140.

Mooning the planets

The search for planetary satellites began in 1610, when Galileo Galilei announced the discovery of four large moons orbiting Jupiter: Io, Europa, Ganymede, and Callisto. New discoveries often come from improvements in technology; indeed, the discovery of the four Galilean satellites directly resulted from the invention of the telescope.

The next satellite discovered, Saturn's Titan, was glimpsed first by Christiaan Huygens with an improved telescope of his own design. Ever-increasing telescope sizes, the use of photographic film, and other technological improvements allowed fainter and fainter satellites to be spotted. This culminated in the last ground-based detection of a small irregular moon, Jupiter's Leda, in 1974. In the 1980s and 1990s, spacecraft brought advanced instruments to each of the giant planets in turn and revealed a whole new class of moonlets circling close to their parent planets in and among planetary rings.

New technology drove the discovery of new satellites by Gladman and his colleagues, as well as the wave of subsequent findings. Replacing photographic film with CCDs (charge-coupled devices) radically improved the sensitivity of astronomical observations. The recent advent of large CCD arrays with tens of millions of pixels has made possible systematic mapping of large regions of sky. Ground-based satellite searches today use 10,000 x10,000-pixel CCD arrays capable of covering a quarter-square-degree patch of sky (roughly equivalent to the Full Moon) in a single exposure.

Searches for satellites from the ground neatly dovetail with space-based ones. Where the latter are superior at finding small satellites close to their planets, the former are better suited for efficiently searching regions farther away.

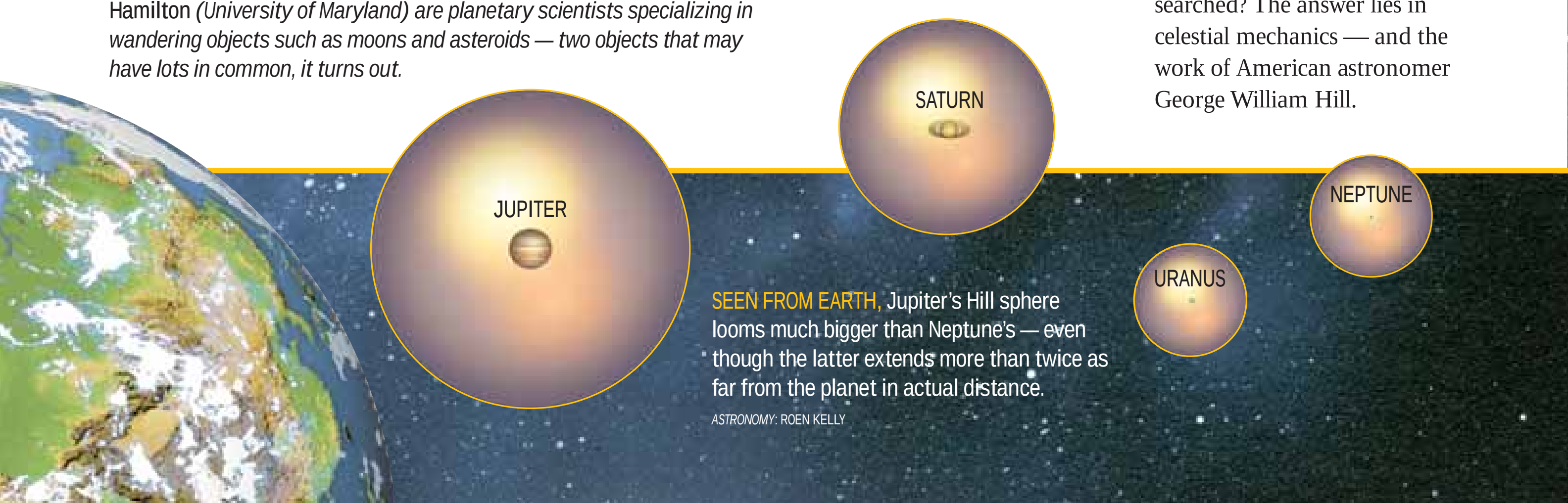
The reasons are geometric. A spacecraft flying close to a planet can focus its cameras on a potential satellite while keeping the much brighter planet out of the field of view, much as a person standing near a bright lamp can turn away to spot a nearby firefly. When viewed from a great distance, however, the light from the planet and the satellite cannot be separated easily. Instead, the bright object's glare overwhelms the faint one because they lie close together.

Despite this, searches for satellites work best from large distances. The person near the lamp must look in all directions to find nearby fireflies, while a more distant observer needs to look only in its general direction to see fireflies circling the lamp.

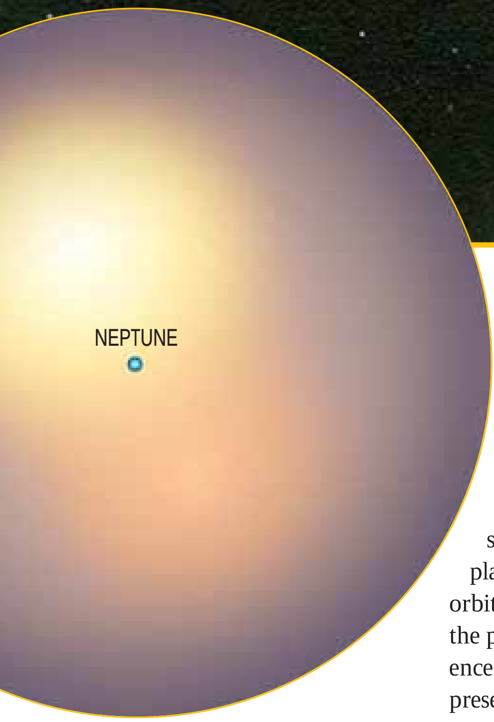
Similarly, telescopes on Earth need to map only a small region of sky around a planet to find new moons rather than the full sky a spacecraft must search. In addition, large-aperture telescopes on Earth are immensely more powerful than the much smaller ones carried by spacecraft. Better instruments and a smaller area of sky to search from Earth more than make up for the advantage in proximity that a spacecraft enjoys.

But how much sky must be searched? The answer lies in celestial mechanics — and the work of American astronomer George William Hill.

Dan Durda *(Southwest Research Institute, Boulder, Colorado) and* Doug Hamilton *(University of Maryland) are planetary scientists specializing in wandering objects such as moons and asteroids — two objects that may have lots in common, it turns out.*



SEEN FROM EARTH, Jupiter's Hill sphere looms much bigger than Neptune's — even though the latter extends more than twice as far from the planet in actual distance.
ASTRONOMY: ROEN KELLY



Spheres of influence

Hill grew up on a farm in West Nyack, New York. As a student of mathematical astronomy at Rutgers College in the late 1850s, he studied the classic works of celestial mechanics. These included Pierre-Simon Laplace's *Méchanique Céleste*, Joseph Louis Lagrange's *Méchanique Analytique*, and what was perhaps the most influential book in Hill's young career, Charles-Eugènes Delaunay's *Théorie du Mouvement de la Lune*.

While on the staff of the *American Ephemeris and Nautical Almanac*, Hill worked for many years on accurately calculating the Moon's orbit and its long-term stability. There, he developed mathematical techniques for describing orbital motions in a system of three bodies (for example, a moon orbiting a planet that itself circles the Sun). These techniques also outline the region around a planet where a moon can keep a stable orbit.

Today, astronomers call this region the Hill sphere. Far down inside a planet's Hill sphere, a moon's orbital motion is dominated by the planet's gravitational influence. The Sun's gravity is still present, but its pull is minor compared to the more powerful tug of the much closer planet.

Moons deep in a planet's Hill sphere have stable orbits, while those orbiting farther out feel more of the Sun's gravitational influence and less of the planet's. Eventually, there comes a point — the edge of the Hill sphere — where the Sun's effect begins to dominate. Beyond this distance, a moon cannot stably orbit the planet. Instead, it will slip away and follow its own path around the Sun.

The size of a planet's Hill sphere depends both on the planet's mass and its distance from the Sun. A large planet like Jupiter reigns gravitationally supreme over a vast region of space, while a small planet such as Mars has a much lesser sphere of influence. For planets with equal masses, those closer to the Sun have smaller Hill spheres than those orbiting farther away.

NASA/JPL/SSI

OBJECTS THAT HAVE LIVED a knockabout life usually wear their past on their faces, and Phoebe is no exception. The heavy cratering it shows testifies to many billions of years of impacts as Phoebe journeyed from the Kuiper Belt, where scientists think it formed, to its present orbit among Saturn's collection of moons.

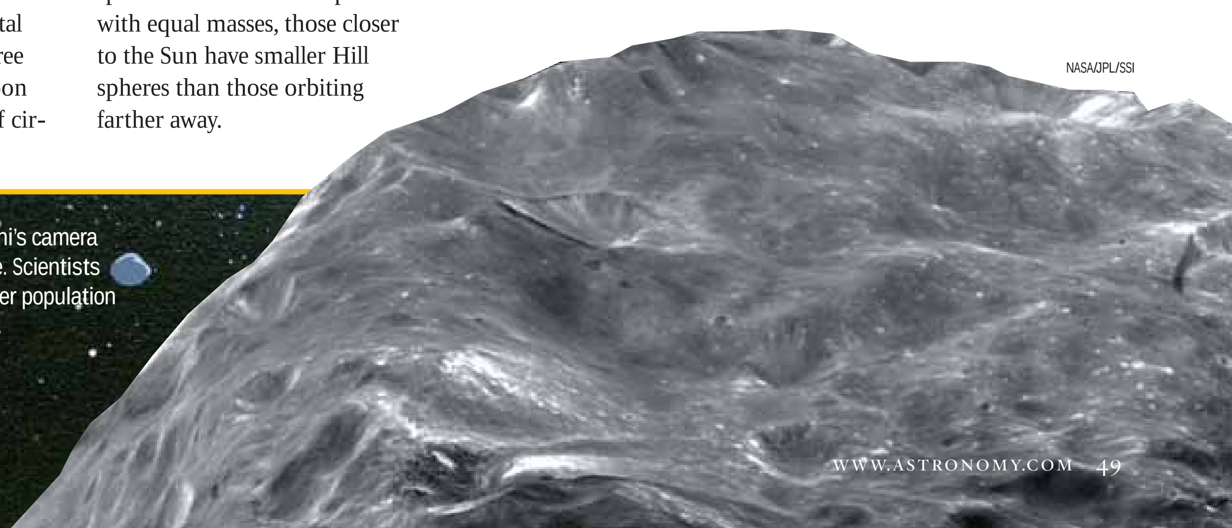
Searching space

As seen from Earth, the areas of sky covered by the Hill spheres of Jupiter, Saturn, Uranus, and Neptune are 48, 22, 6, and 7 square degrees, respectively. These are small compared to the 41,000-square-degree area of the full sky that an *in situ* spacecraft would have to search.

But ground-based observers still have to stitch together a lot of quarter-square-degree images to cover a planet's entire Hill sphere. This is one practical reason why Gladman's team focused its initial satellite searches on the neighborhoods of Uranus and Neptune rather than Jupiter and Saturn.

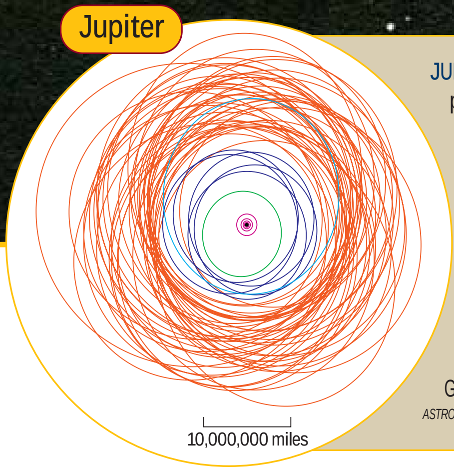
Investigating the most distant planets comes with a price, though. The moons of far-off planets shine more faintly and are more difficult to spot than those nearby because the sunlight they reflect drops off rapidly with increasing distance from the Sun. For example, a 1-mile-diameter moon orbiting Jupiter appears as bright as a 4-mile moon at Saturn, a 16-mile moon at Uranus, and a 36-mile moon at Neptune.

Of the 75 new moons discovered over the last several years, most are smaller than about 6 miles across. The largest of the new satellites is 120-mile-diameter (190 kilometer) Sycorax orbiting Uranus, while the smallest new satellites, spotted at Jupiter, are barely half a mile across.



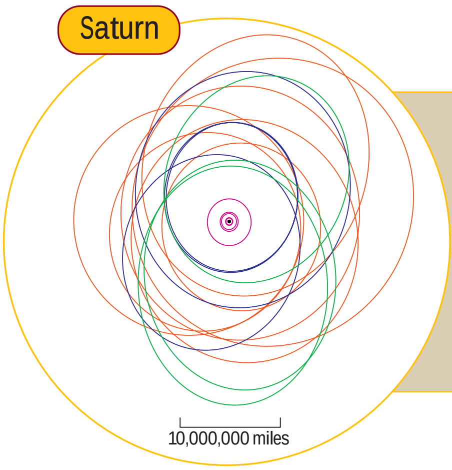
NASA/JPL/SSI

CLOSE UP ON PHOEBE, Cassini's camera imaged a battered landscape. Scientists are studying the moon's crater population for clues to Phoebe's history.

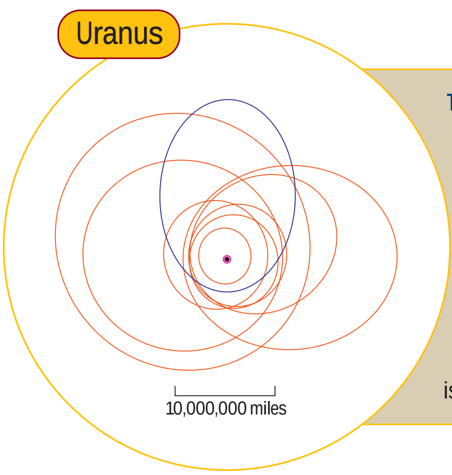


JUPITER'S MOONS wrap the planet in an ever-shifting orbital network. The orbits in red go retrograde — clockwise as seen here — unlike the regular moons (other colors) that orbit in the same direction Jupiter rotates. The innermost (pink) orbits belong to Io, Europa, Ganymede, and Callisto.

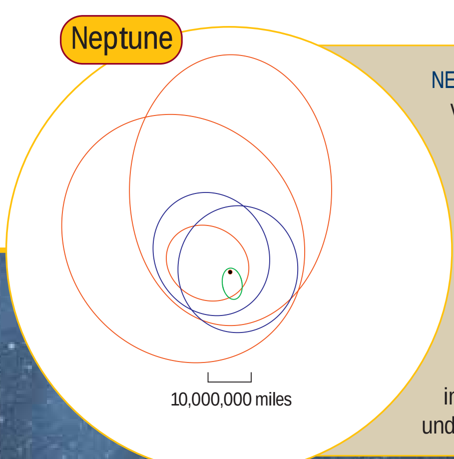
ASTRONOMY: ROEN KELLY/SCOTT SHEPPARD, CIW



THE SATURNIAN IRREGULAR MOONS belong to several groups (coded by color). The outermost pink orbit is that of Iapetus. Note the large gap between Iapetus and the innermost irregular moons.



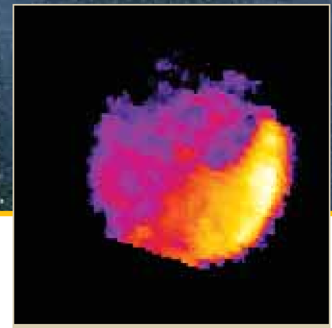
THE IRREGULAR MOONS OF URANUS weave a loose pattern around the regular moons, shown in pink. Although Uranus has only a sixth the mass of Saturn, its moon swarm reaches about as far into space because the Sun's gravity is weaker there.



NEPTUNE'S MOONS include 7 vagabonds and 6 regulars close to the planet. The small number comes from search difficulties caused by Neptune's distance from Earth. Its Hill sphere spans more than twice Jupiter's, and Neptune orbits near the Kuiper Belt of icy planetesimals. It could have many undiscovered moons.

NASA/JPL/UNIV. ARIZONA

PHOEBE'S SURFACE displays a variety of materials as mapped by Cassini's spectrometers. Exposures of water ice appear blue, carbonaceous material is red, and a second carbonaceous "mystery material" (not yet identified) appears green.



NASA/JPL/GSFC

COLD DOMINATES the surface of Phoebe, which has a peak temperature of 107 kelvins (–267° Fahrenheit), shown in white. The coldest temperature Cassini detected (purple) was found on the nightside: 75 kelvins, or –324° F.

Patterns in the sky

The flurry of new satellite discoveries (75 in all) reveals some patterns that planetary scientists are using to probe the outer solar system's history.

Nearly two-thirds of the known moons, including all the recent discoveries, are irregular satellites. These orbit far from their planets along highly tilted, elliptical paths. (Many irregulars also orbit retrograde, opposite the direction followed by the planets themselves.)

In particular, the orbital distributions of Jupiter and Saturn's irregular moons hint at past interactions and collisions. When the giant planets were forming, dense envelopes of gas surrounded each, feeding the growing bodies. Asteroidal objects born elsewhere in the solar system flew closely past the embryonic planets. Encountering the gas, they were slowed by friction, and at least some became captured. Collisions among these vagabond moons subsequently thinned their numbers and left the planets with orbiting fragments for scientists to study today.

For example, at Jupiter, all but one of the newly found irregular objects orbit retrograde. At Saturn, however, distant prograde and retrograde moons appear in roughly equal numbers. Furthermore, their orbital tilts are not random: They're grouped into associations that imply a common origin for a group's members.

The associations resemble the minor-planet families in the main asteroid belt, which are the remains of large parent bodies that broke apart ages ago.

Another pattern is that none of the 75 new moons circles a terrestrial planet. (One search of Mars' Hill sphere would have found any undiscovered inner satellite bigger than 100 yards across.) This comes as no surprise. Terrestrial planets orbit the Sun more closely than the gas giants (thus reducing their Hill spheres' extent), and even the most massive terrestrial planet (Earth) has only 7 percent the mass of the lightest gas giant (Uranus). Small masses plus solar proximity equals small Hill spheres.

Yet the real picture is a little more complicated. Terrestrial planets actually can have a kind of vagabond moon. Recent theoretical and computational work has turned up asteroids that are not currently satellites of the terrestrial planets — but which have been in the past and will be again in the future. Most of these are natural objects, asteroids that wandered into the inner solar system and were temporarily captured.

At least one, however, is almost certainly artificial. In September 2002, amateur observer Bill Yeung discovered an unusual, fast-moving object near Earth that appeared to be orbiting our planet about twice as far away as the Moon.

At first, it seemed J002E3 was the only known case of a small asteroid captured into orbit around Earth. But analysis of its pre-capture orbit and solar-radiation pressure's effects on its trajectory proved that J002E3 is manmade. It's the S-IVB third stage from Apollo 12, which returned home after a 33-year "walkabout" through the inner solar system.

Close-up views

To scientists, the wayward moons of the outer solar system have long been just featureless points of light circling distant planets. Yet this picture began to change June 11, 2004, when the Cassini spacecraft, en route to arrive at Saturn 3 weeks later, flew past the planet's tiny, irregular moon Phoebe.

Cassini's instruments revealed a unique and alien world, potato-shaped and heavily crater-pocked. Dark organic material overlies a buried icy layer partly exposed to view inside deep-penetrating craters. Cassini spotted bright streaks and rays associated with craters, and found long grooves and other linear features.

Phoebe's density is 1.6 times that of water, a low value implying large amounts of ice and, perhaps, a somewhat porous exterior. Oddly (and probably coincidentally), Phoebe's rotation period, 9 hours and 16 minutes, gives it a day not much different than Saturn's.

Scientists looking to unravel the origins of irregular satellites are focusing closely on Phoebe's crater population. These scars from ancient impacts give a glimpse into this mysterious object's violent past.

NASA/JPL/SSI

GEOLOGICAL DETAILS APPEAR in this 8-mile-diameter (13 km) crater on Phoebe — building-size boulders litter the crater's floor, while bright splashes mark recent impacts and landslides. Scientists hope such details will help them better understand Kuiper Belt objects.

Some craters came from comets passing through the saturnian system, while others may have come from material in orbit around Saturn. The five additional small moonlets in Phoebe's family came from at least one large impact, evidence of which may still be visible on Phoebe's surface. What fraction of the moonlets created in such a titanic event came back one day — billions of years later — to reimpact its parent satellite? How many will do so in the distant future?

Cassini won't return to survey Phoebe again — it lies too far from the spacecraft's trajectory for the rest of the mission. But scientists studying irregular moons have another target in mind for an upcoming mission.

The New Horizons mission to Pluto and the Kuiper Belt is scheduled to launch in January 2006. In February 2007, the spacecraft will attempt a close flyby of one of Jupiter's small irregular satellites. If successful, this will bring into close-up focus another distant point of light in the sky.

The irregular moons of the giant planets are the hoboes of the Hill sphere — vagabonds that come and go as dictated by gravity. With origins far from their present homes, they intrigue scientists with the messages they bring from distant parts of the solar system. Studying them in detail will give us a better look at how the planetary system we call our own was born. A

Find out how planetary scientists study vagabond moons and their origins at www.astronomy.com/toc

/// MOONS, VAGABOND AND OTHERWISE

PLANET	REGULAR MOONS	IRREGULAR MOONS	TOTAL MOONS
Jupiter	8	55	63
Saturn	19	14	33
Uranus	18	9	27
Neptune	6	7	13