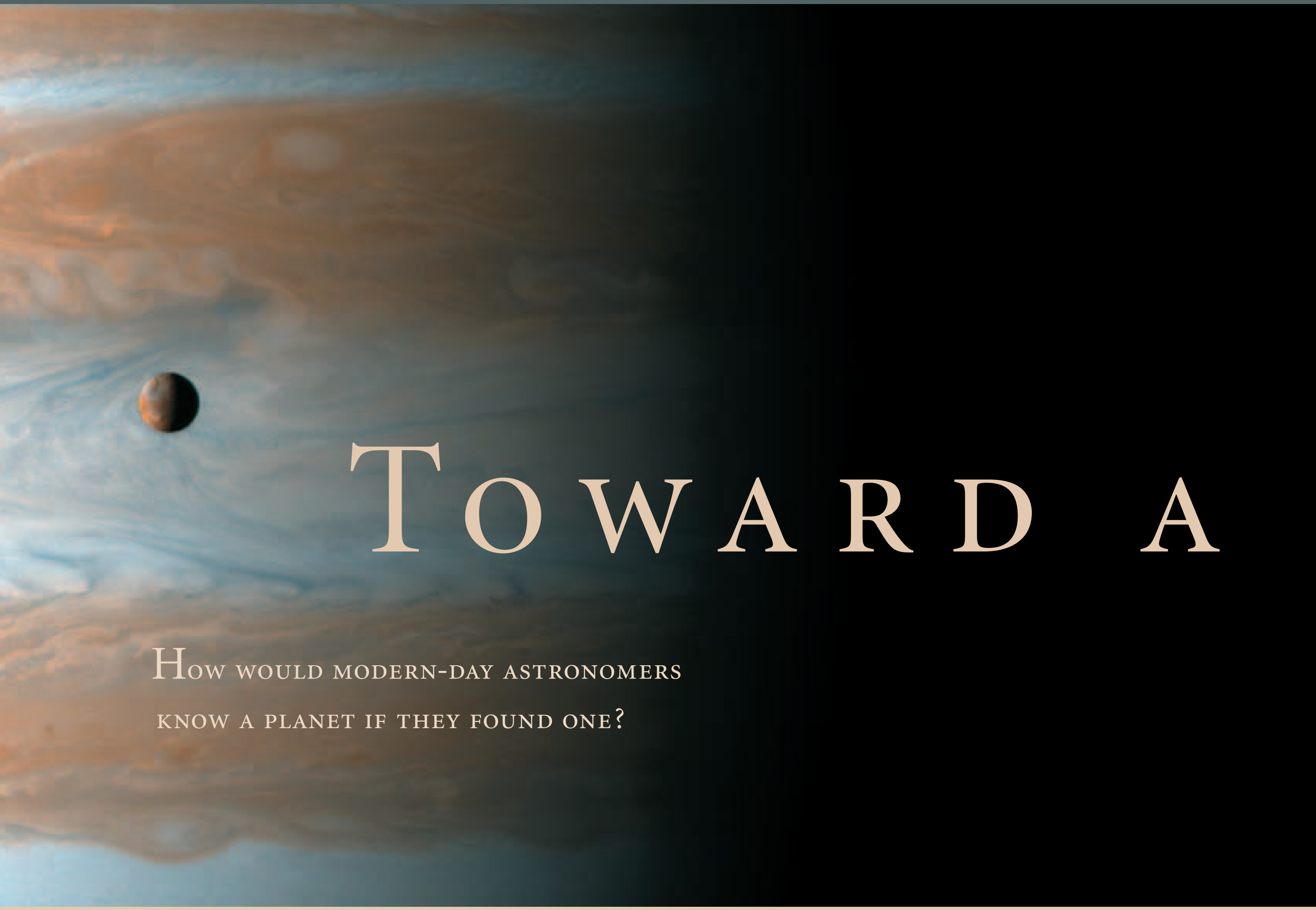


Toward a

How would modern-day astronomers know a planet if they found one?

Deciding how bodies in planetary systems should be classified seemed easy little more than a decade ago. Among the small objects, comets showed tails and asteroids did not. Regarding the planets, there were nine: four terrestrials, four gas giants, and Pluto. The story was pretty straightforward, and no one, not even the International Astronomical Union (IAU), found the need to define the obvious.

But then new facts and observations intruded into this clearly naive view. By the 1990s it had become clear that our solar system was a messy, mixed bag of bodies. The interior structures and compositions of Jupiter and Saturn proved distinct from those of Uranus and Neptune, enough so that aficionados felt obliged to subtype these pairs as "gas giants" and "ice giants." And we realized that a handful of objects now classified as asteroids, like 2060 Chiron and 4015 Wilson-Harrington, sporadically exhibit cometlike comas. One ostensible asteroid, 1996 PW, was even found coming from the Oort Cloud, the presumed reservoir of long-period comets.

To make matters more confusing, astronomers detected planetary-mass objects orbiting a pulsar. Then came massive "hot Jupiters" circling implausibly close to their host stars. The list of aberrant oddities grew longer, blurring the simple boundaries and colloquial definitions that planetary astronomers had used in textbooks and in their research. As our science grew more mature, simple black-and-white notions dissolved into a spectrum of myriad shades of gray.

The situation came to a head over Pluto — or rather the realization that Pluto exists among a cohort of more than 100,000 miniature worlds collectively called the Kuiper Belt. Over the decades, we'd come to accept that Pluto was nowhere near the Earth-size body imagined after its discovery in 1930. But by the mid-1990s, as the count of Kuiper Belt objects (KBOs) in orbits like Pluto's grew, it became apparent to many researchers

> *"What's in a name?*
> *That which we call a rose by any other name would smell as sweet."*
>
> *— William Shakespeare*
> Romeo and Juliet, *act 2, scene 2*

Planet Paradigm

By S. Alan Stern and Harold F. Levison

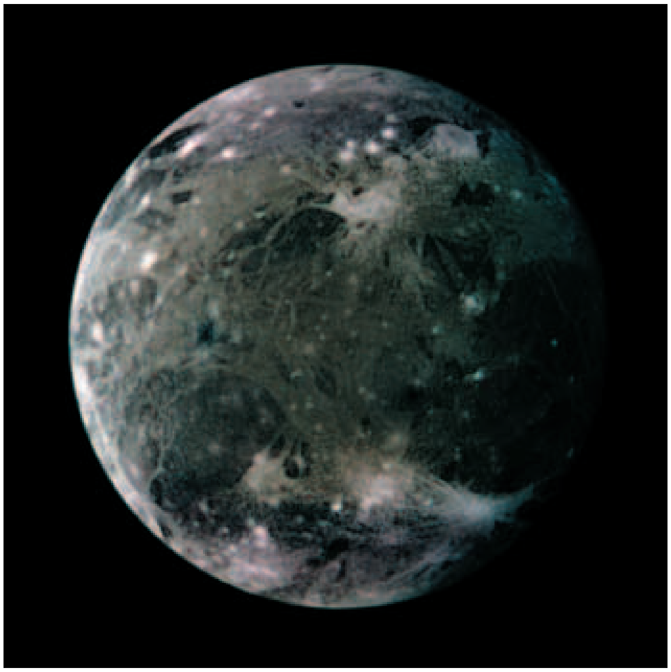
that the ninth planet was instead the "King of the Kuiper Belt."

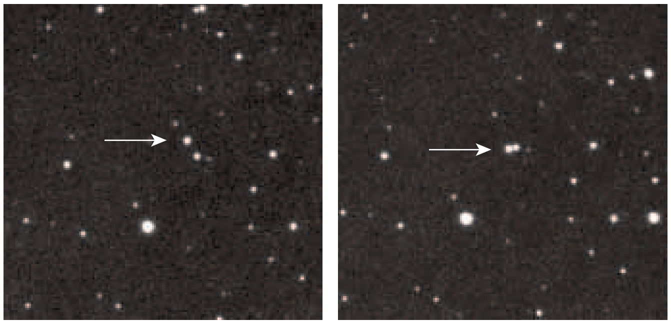
A few astronomers began to question aloud whether this far-flung world should be "demoted" to minor-planet status. Besides Pluto's association with the Kuiper Belt, they noted, it is smaller than many planetary satellites. Planethood proponents countered that it is a world with its own personality and its own story to tell. The hue and cry intensified in early 1999, reaching such a fever pitch that friendships were strained over it. The Internet sizzled with testy accusations, and impassioned editorials appeared in print. Schoolchildren wrote essays in defense of the poor little world. The debate grew so vociferous that Johannes Andersen, the IAU's General Secretary, was compelled to issue a statement confirming Pluto's status as a planet (*S&T:* May 1999, page 51).

This wasn't the first time astronomers have disagreed on planetary pedigrees. When Giuseppe Piazzi spotted Ceres in 1801, he was immediately hailed for discovering the "missing" planet that had been predicted by the Titius-Bode law to lie between Mars and Jupiter (*S&T:* February 2001, page 49). But Piazzi himself soon had doubts about the size of his find, and the following year, following the discovery of a second interloper beyond Mars (Pallas), William Herschel deduced that these bodies were only hundreds — not thousands — of miles across. Eventually, as the list of such bodies grew, even the most ardent Titius-Bode supporters were forced to accept that these were not major planets. Today the count of numbered asteroids and other minor planets stands at more than 40,000.

So what's in a name? How much should we care about whether one object is called a planet and another is not? After

***Facing page:* The sheer breadth of the solar system's "planetary" bodies was dramatically captured by the Cassini orbiter on January 1, 2001. The clouds of Jupiter loom in the background behind Io (far left), the planet's most dynamic moon. Courtesy NASA/JPL/University of Arizona.**





Above: **Although reduced to a faint blip in these discovery images, the distant Kuiper Belt object 28978 Ixion appears to be at least 1,200 km across — decidedly larger than the largest asteroid, 1 Ceres. Courtesy Marc Buie (Lowell Observatory) and the Deep Ecliptic Survey.**

Left: **Ganymede is the largest moon in the solar system. With a diameter of 5,268 kilometers, it tops both Mercury and Pluto in size and has three-fourths the girth of Mars. It also has an intrinsic magnetic field and a tenuous atmosphere. Thus many astronomers think of Ganymede essentially as a planet that happens to orbit Jupiter. Courtesy NASA/Jet Propulsion Laboratory.**

all, Pluto will still be Pluto no matter what else we call it. However, scientists have always put things in bins, and it is healthy for us to do so. Having well-defined categories lets us communicate more easily with one another and also with the public. But sometimes the situation forces change, and it can be painful. Once the paradigm shift is made, however, communication becomes smooth again.

No one is more painfully aware of this philosophy than Michael F. A'Hearn (University of Maryland), who in 1999 headed the IAU division that deals with planetary-system science — and thus stands at the center of the dispute over Pluto. "Scientists classify things in order to find patterns that will help explain how things are related or how they evolved," A'Hearn writes, and that process is not always easy or quick. He points to the protracted debate over whether the archaeopteryx, a flying creature that inhabited Earth 145 million years ago, should be classed as a bird, a dinosaur, or both. Fossils discovered in the mid-1800s show that the archaeopteryx had feathers, a wishbone, and birdlike hind limbs — but it also had teeth and a bone structure more like those of dinosaurs. Today, more than a century after its discovery, paleontologists continue to squabble.

Setting the Ground Rules

So how should we apply these lessons and all this new information to our definition of planethood? In a word, carefully. The solar system is much too complicated for simple answers. There are many ways to define planethood, each of which would give very different results. One suggestion, bandied among some astronomers, proposed that anything orbiting the Sun and at least 2,000 kilometers across is a planet. By this definition, our solar system has nine of them. However, we and others contend that the 2,000-km criterion is arbitrary, a value of convenience chosen to fit our situation. If instead we were to devise a physically meaningful definition, our solar system would almost certainly not end up with nine planets; depending on the chosen characteristics, we would have more of them or fewer, but not nine. Taken to extremes, one can even imagine a scenario in which Jupiter and Saturn are defined as "failed stars," Uranus and Neptune as "planets," and everything else as simply "junk."

In light of the recently strident discussion about what does and does not constitute a planet, it's fair to ask whether such a physically based algorithm could be drawn up — let alone agreed to. To that end, we have taken up the challenge in a paper to be published in the *Transactions* of the International Astronomical Union. In our view, such an algorithm should

- *be based on easily observed characteristics:* Our decisions should be driven by observable physical characteristics like mass or diameter and not depend on poorly understood or poorly determinable concepts such as mode of origin;
- *be quantitative:* The results should be based on numerical properties or parameters of the bodies being categorized;
- *be robust to new discoveries:* The algorithm should be general enough to accommodate at least some unexpected discoveries, such as binary and trinary planets, or free-floating bodies that have escaped their parent stars;
- *classify uniquely:* No body should end up with multiple classifications;
- *be context independent:* An object's classification should not depend upon the nature of other bodies in its vicinity;
- *be uniquely deterministic:* Once categorized, no body should have its status change with time, such as when it acquires or loses an atmosphere, magnetic field, or satellites; and
- *involve the fewest possible criteria:* The algorithm should be "fat free."

In addition, it would be best if such a test were "backward compatible," within reason. That is, it should avoid numerous reclassifications within our solar system. While we don't insist on this attribute, ultimately a viable test for planethood shouldn't confuse people. Given these precepts, the table on the facing page offers a few examples of what *doesn't* work.

Unsatisfactory Planetary Classification Criteria

Criterion	*Problem or Counterexample*
Presence of satellites	Omits Mercury, Venus; can be time-dependent
Presence of an atmosphere	Omits Mercury; problem due to definition of minimum atmosphere
Presence of a magnetic field	Omits Venus and perhaps Pluto
Orbits a star	Omits ejected planets; allows all asteroids and comets; can be time-dependent
Reflects more light than it generates	Omits Jupiter, Saturn, and Neptune now; allows dust

The Envelope, Please

Our recommended algorithm for determining planethood attempts to incorporate all the desirable attributes we've detailed. It consists of two simple criteria, both of which are based on the body's mass; these criteria together define planetary bodies to be a class of objects sandwiched between bodies that are too large (protostars, stars, or stellar remnants, depending on their stage of evolution) and those that are too small (planetesimals, rocks, and dust).

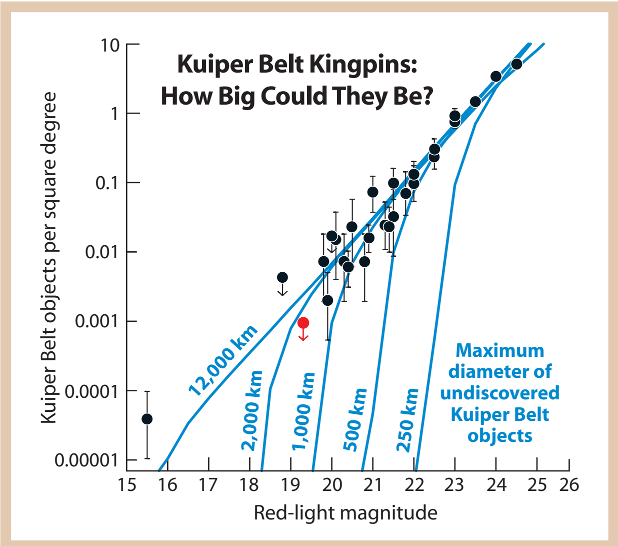
At the "large" size end, the body must be low enough in mass that *at no time,* past or present, can it generate energy in its interior due to any self-sustaining fusion reaction. Otherwise we would consider it a brown dwarf or a star (see page 32).

At the "small" end, the body must be massive enough that its shape is determined primarily by gravity rather than by mechanical strength or other factors like surface tension or rapid rotation. This shape need not be strictly a sphere — a rapid spinner would conform to a distinctly oblate ellipsoid, as is the situation with Jupiter and Saturn. Our emphasis on the rule of mass, and hence self-gravity, has the ancillary benefit of eliminating nearly spherical objects controlled by surface tension or by electromagnetic or electrostatic forces. Also, we'd allow our candidates enough time (basically, the age of the universe) to reach their equilibrium shape. Thus there can be a period early in the body's evolution when gravity may not yet have fully manifested itself in controlling shape.

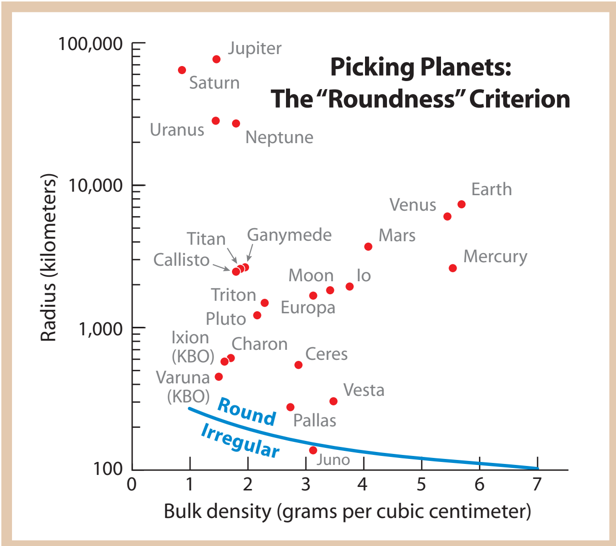
By our criteria, planetary bodies span a very wide range of masses, from roughly a thousandth that of Earth to nearly 10,000 Earths (a factor of 10^7). Admittedly, these are broad limits — stars have a much narrower spread of masses ($10^{4.2}$) — though ours is not unlike the range exhibited by galaxies (about 10^6).

Even so, our algorithm offers some nice advantages. Planethood would be bestowed on a measurable or estimable characteristic: mass. Moreover, any body can be evaluated quantitatively to yield a unique result (yes or no) that is independent of time and the body's location. Finally, our algorithm for planethood is insensitive to factors such as whether the candidate body has satellites, a magnetic field, or an atmosphere.

But can our criterion be determined through observation? Generally, yes, because mass can manifest itself in many ways.



DATA SOURCE: C. TRUJILLO (CALTECH)



DATA SOURCE: S. A. STERN AND H. F. LEVISON (SOUTHWEST RESEARCH INSTITUTE)

Left: **Recent telescopic surveys of the Kuiper Belt have turned up a few objects comparable to the largest asteroids in size, but might another "Pluto" await discovery? Chadwick A. Trujillo (University of Hawaii) and others suspect so, though they must rely on theoretical extrapolations from the population of objects discovered to date. One photographic survey (red dot), conducted by Charles Kowal in the 1970s, suggests that there are no undiscovered KBOs within 70 a.u. of the Sun more than about 1,800 km across — well below the size of Pluto. *Right:* What if planethood were decided based only on whether a body had enough mass to assume a round shape (solid line), as the authors propose? Then at least 20 objects in our solar system — including the Moon, Vesta, and the Kuiper Belt's Ixion — would qualify.**

For example, we may deduce an object's mass directly, by the degree to which its gravity perturbs neighboring bodies, visiting spacecraft, or (as is the case for extrasolar planets) its central star.

Other clues may come from its diameter and presumed composition. We've now seen Ceres with enough resolution to know that it is about 950 km across (January issue, page 21), and its overall density is roughly 2.6 grams per cubic centimeter. This suggests that Ceres has enough mass to have rendered itself more or less round and would thus count as a planetary body. Objects in the Kuiper Belt are, for now, too distant to resolve telescopically, but we can estimate their diameters using their apparent magnitudes and assumptions about surface reflectivity. The recently discovered object 28978 Ixion (formerly 2001 KX_{76}) is at least 1,200 km across and may be as large as 1,400. Assuming it consists of a fairly solid mixture of ice and rock, it too would qualify for planethood.

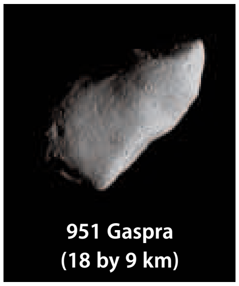
In fact, as shown at lower right on the preceding page, at least 20 known bodies in our solar system already meet our criterion for gravity-dominated shape, based on their diameters and bulk densities. Notice that large KBOs (including Pluto) and the very largest asteroids make the cut: while they may be "minor" planetary bodies or satellites, they are nonetheless planets in essence. As in life, we prefer to be inclusive, rather than exclusive.

Notice that by our definition, both large satellites of planets, as well as objects freely floating in interstellar space, qualify as planetary bodies (a term we consider to represent the intrinsic nature of a body). We therefore need to make some further distinctions.

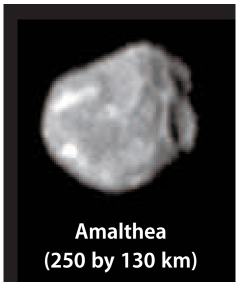
We propose that a *planet* is any planetary body bound in an orbit around a single or multiple-star system. By this definition, the classical nine planets, as well as a few of the largest asteroids, and very large KBOs qualify in our solar system. An *unbound planet* is any planetary body not orbiting a single or a multiple-star system. A *planetary-scale satellite* is any planetary body permanently orbiting a larger planetary body on a bound orbit; examples of planetary-scale satellites include Earth's Moon, all four Galilean satellites, Titan, and Triton. And finally, a *double planet* would consist of a planet and a satellite massive enough to place the system's center of gravity somewhere between the two bodies. Pluto-Charon is the only such example in our solar system.

Whether the IAU adopts any classification system for planets, including ours, is yet to be determined. Typically its various commissions and working groups resolve issues like this one slowly and conservatively. Until then we, and you, will just have to be patient with the current confusion. As Lord Halifax once wrote, "A man that should call everything by its right name, would hardly pass the streets without being knocked down as a common enemy."

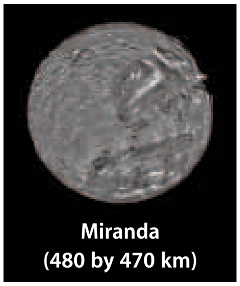
The larger and more massive the body, as these examples show, the more likely that self-gravity will have molded it into a round shape.



951 Gaspra (18 by 9 km)



Amalthea (250 by 130 km)



Miranda (480 by 470 km)

NASA/JPL (3)

ALAN STERN *directs the Southwest Research Institute's Department of Space Studies in Boulder, Colorado, and serves as principal investigator of NASA's New Horizons mission to Pluto and beyond.* HAL LEVISON, *a staff scientist at SwRI-Boulder, specializes in the dynamical evolution of the solar system.*

A Starring Role for Dynamics?

"Just because your doctor has a name for your condition, doesn't mean he knows what it is."

— Franz Kafka

There's more than one way to skin a cat, and by the same token there's more than one way to use an object's mass to determine its viability as a planet. Beyond our strict "yes/no" determination described in the accompanying article, it's also valuable to establish a classification scheme that recognizes whether a given body is dynamically important to the system in which it resides.

For example, the census of known planetary-scale (read: rounded due to gravity) bodies in heliocentric orbit includes the four large terrestrial bodies, two giant planets, two ice giants, about 20 large asteroids, and hundreds of large Kuiper Belt objects (including Pluto). But the largest and smallest members of this class clearly play different roles in shaping the solar system's dynamical structure. After all, while some might consider Io to qualify as a planetary body, it orbits deep within the gravitational well of Jupiter.

Distinguishing among worlds on some dynamical basis is both useful and desirable to help us understand the architecture and evolution of our solar system. The goal, then, is to determine whether any given planetary body is dynamically important to the system in which it is found. So let's consider an *überplanet* to be an object, orbiting a star, that has cleared away its neighboring planetesimals through gravitational interactions over the age of the universe (which obviously, for many young systems, will extend far into the future). And we define an *unterplanet* as one that is not able to do so.

Applying this test, we know that our solar system contains eight überplanets and a far larger number of unterplanets, the largest that we know of being Pluto and Ceres. Natural satellites, regardless of their size or mass, would automatically be classed as unterplanets because they are at the gravitational mercy of the planets they orbit. However, were Earth's Moon to orbit the Sun on its own at a distance of 1 astronomical unit, it would qualify for überplanet status.

So someday planetary bodies, here or elsewhere, might well be categorized by some combination of "roundness" and dynamical clout, both of which are proxies for mass. This would yield a two-parameter matrix of subtypes that loosely parallels stellar terminology. For sorting by mass, we suggest the categories *subdwarf, dwarf, subgiant, giant,* and *supergiant.* For composition, we'd propose the generic terms *"rock," "ice,"* and *"hydrogen gas,"* to represent, in gross terms, the body's primary constituent. These compositional types could be expanded if new discoveries warranted doing so.