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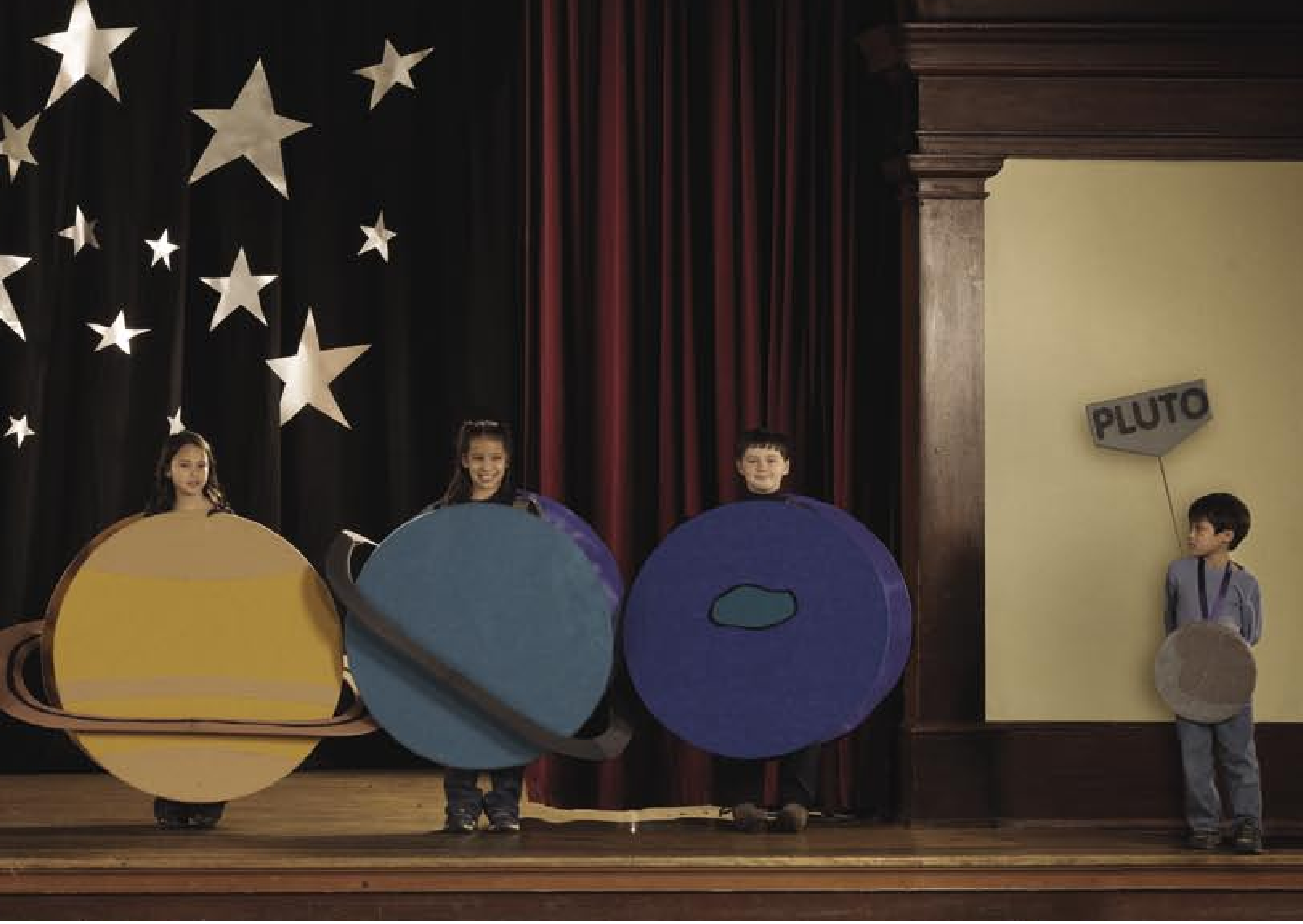
WHAT IS A PLANET?

By Steven Soter

The controversial new official definition of "planet," which banished Pluto, has its flaws but by and large captures essential scientific principles

Most of us grew up with the conventional definition of a planet as a body that orbits a star, shines by reflecting the star's light and is larger than an asteroid. Although the definition may not have been very precise, it clearly categorized the bodies we knew at the time. In the 1990s, however, a remarkable series of discoveries made it untenable. Beyond the orbit of Neptune, astronomers found hundreds of icy worlds, some quite large, occupying a doughnut-shaped region called the Kuiper belt. Around scores of other stars, they found other planets, many of whose orbits



look nothing like those in our solar system. They discovered brown dwarfs, which blur the distinction between planet and star. And they found planetlike objects drifting alone in the darkness of interstellar space.

These findings ignited a debate about what a planet really is and led to the decision last August by the International Astronomical Union (IAU), astronomers' main professional society, to define a planet as an object that orbits a star, is large enough to have settled into a round shape and, crucially, "has cleared the neighborhood around its orbit." Controversially, the new definition removes Pluto from the list of planets. Some astronomers said they would refuse to use it and organized a protest petition.

This is not just a debate about words. The question is an important one scientifically. The new definition of a planet reflects advances in our understanding of the architecture of our solar system and others. These systems formed by accretion within rotating disks: small grains clump together to form bigger ones, which draw themselves together to form still bigger ones, and so on. This process eventually produces a small

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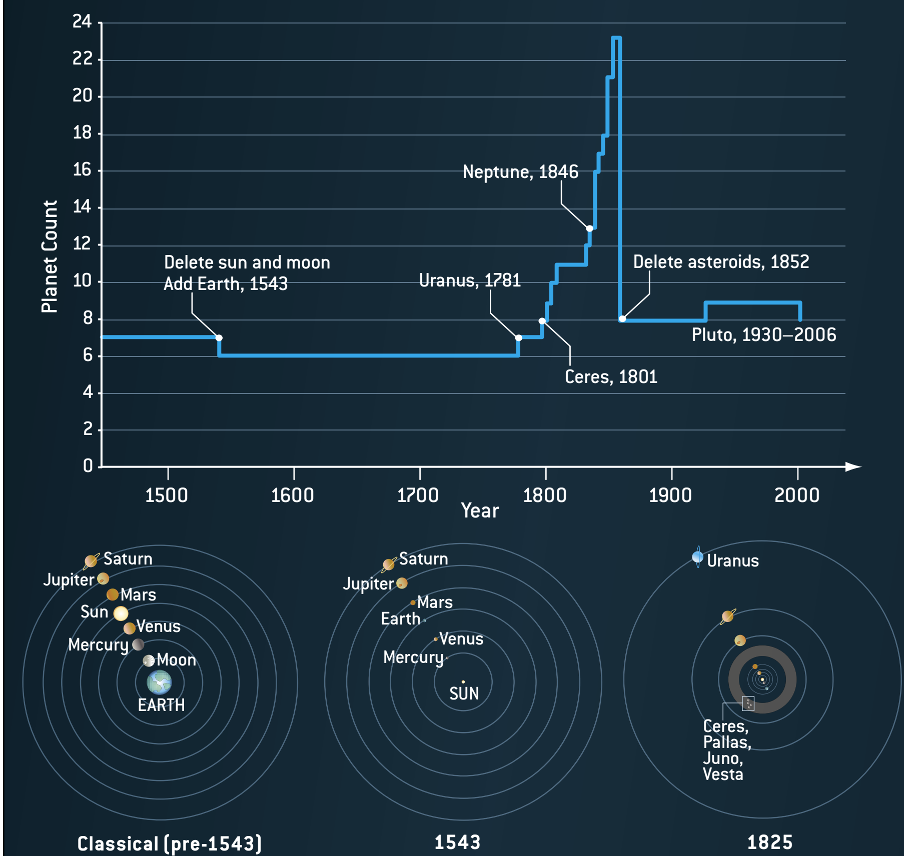
HISTORICAL COUNT OF PLANETS

Planets come, planets go as a result of new discoveries and changing conceptions of what a "planet" is. The decision to recategorize Pluto is simply another step in this historical progression.



DATE	PLANETS
Pre-1543	Mercury, Venus, Mars, Jupiter, Saturn, sun, moon
1543	Earth added sun, moon deleted
1781	Uranus
1801	Ceres
1802	Pallas
1804	Juno
1807	Vesta
1845	Astraea
1846	Neptune
1847	Hebe, Iris, Flora
1848	Metis
1849	Hygiea
1850	Parthenope, Victoria, Egeria
1851	Irene, Eunomia
1852	Asteroids deleted
1930	Pluto
2006	Pluto deleted

number of massive bodies—the planets—and a large number of much smaller bodies—the asteroids and comets, which represent the debris left over from planet formation. In short, "planet" is not an arbitrary category but an objective class of celestial bodies.

When Earth Became a Planet

ASTRONOMERS' reevaluation of the nature of planets has deep historical roots. The ancient Greeks recognized seven lights in the sky that moved against the background pattern of stars: the sun, the moon, Mercury, Venus, Mars, Jupiter and Saturn. They called them *planetes,* or wanderers. Note that Earth is not on this list. For most of human history, Earth was regarded not as a planet but as the center—or foundation—of the universe. After Nicolaus Copernicus persuaded astronomers that the sun rather than Earth lies at the center, they redefined planets as objects orbiting the sun, thereby putting Earth on the list and deleting the sun and moon. Telescope observers added Uranus in 1781 and Neptune in 1846.

Ceres, discovered in 1801, was initially welcomed as the missing planet that filled the gap between Mars and Jupiter. But astronomers began to have doubts when they found Pallas in a similar orbit the following year. Unlike the classical planets, which telescopes revealed as little disks, both these bodies

Overview/*Planet Definition*

- Last August members of the International Astronomical Union voted to define a planet as a body that orbits a star, is large enough to be round, and has cleared other bodies out of its neighborhood. The definition was intended to bring closure to a long-standing debate but instead seems to have poured fuel on the fire.
- Critics have called the definition arbitrary and imprecise, but the charge is unfounded. The solar system divides cleanly into eight bodies massive enough to dominate their orbital zones and swarms of smaller ones that occupy intersecting orbits. This pattern appears to reflect the way the solar system formed and evolved.

LUCY READING-IKKANDA

appeared as mere pinpricks of light. English astronomer William Herschel proposed naming them "asteroids." By 1851 their number had increased to 15, and it was becoming unwieldy to consider them all planets. Astronomers then decided to list asteroids by their order of discovery rather than by distance from the sun, as for planets—the de facto acceptance of the asteroids as members of a distinct population. If we still counted asteroids as planets, schoolchildren studying the solar system would now have to cope with more than 135,000 planets.

Pluto has a similar story. When Clyde Tombaugh discovered it in 1930, astronomers welcomed Pluto as the long-sought "Planet X" whose gravity would account for unexplained peculiarities in the orbit of Neptune. Pluto turned out to be smaller not only than the other eight planets but also than seven of their satellites, including Earth's moon. Further analysis showed the peculiarities in Neptune's orbit to be illusory. For six decades, Pluto was a unique anomaly at the outer edge of the planetary system.

Just as Ceres began to make sense only when it was recognized as one of a vast population of asteroids, Pluto fell into place only when astronomers found it was one of a vast population of Kuiper belt objects (KBOs) [see "The Kuiper Belt," by Jane X. Luu and David C. Jewitt; Scientific American, May 1996, and "Migrating Planets," by Renu Malhotra; Scientific American, September 1999]. Astronomers began to reconsider whether it should still be called a planet. Historically, revoking the planetary status of Pluto would not be unprecedented; the ranks of ex-planets include the sun, moon and asteroids. Nevertheless, many people have argued for continuing to call Pluto a planet, because almost everyone has grown quite accustomed to thinking of it as one.

The discovery in 2005 of Eris (formerly known as 2003 UB313 or Xena), a KBO even larger than Pluto, brought the issue to a head. If Pluto is a planet, then Eris must also be one, together with scores of other large KBOs; conversely, if Pluto is not a planet, neither are the other KBOs. On what objective grounds could astronomers decide?

Clearing the Air

To avoid an open-ended proliferation of planets, Alan Stern and Harold Levison of the Southwest Research Institute suggested in 2000 that a planet could be defined as a body less massive than a star but large enough for its gravity to overcome its structural rigidity and pull it into a round shape. Most bodies larger than several hundred kilometers in radius satisfy the latter criterion. Smaller ones often have a craggy shape; many of them are basically giant boulders.

This definition was the one advocated in early August by the IAU Planet Definition Committee, chaired by Owen Gingerich of Harvard University. It would have retained Pluto as a planet, but at the expense of admitting potentially dozens of KBOs and restoring the planetary status of Ceres, the largest asteroid and the only one known to be spherical.

Many astronomers argued that the roundness criterion is inadequate. In practical terms, it is very difficult to observe the shapes of distant KBOs, so their status would remain ambiguous. Furthermore, asteroids and KBOs span an almost continuous spectrum of sizes and shapes. How are we to quantify the degree of roundness that distinguishes a planet? Does gravity dominate such a body if its shape deviates from a spheroid by 10 percent or by 1 percent? Nature provides no unoccupied gap between round and nonround shapes, so any boundary would be an arbitrary choice.

Stern and Levison proposed another criterion that does, however, lead to a nonarbitrary way to classify objects. They remarked that some bodies in the solar system are massive enough to have swept up or scattered away most of their immediate neighbors. Lesser bodies, unable to do so, occupy transient, unstable orbits or have a heavyweight guardian that stabilizes their orbits. For

FREQUENTLY ASKED QUESTIONS

Q Isn't the definition of a planet really arbitrary?

A Scientists need precise definitions to communicate effectively. Careful definitions reflect our understanding of basic relationships in nature. If new discoveries render an old definition misleading or obsolete, we need to revise it accordingly.

Q What's wrong with the old definition of a planet as a nonluminous body orbiting a star and larger than an asteroid?

A It makes no distinction between planets and Kuiper belt objects, even though they are clearly different.

Q The definition approved by the International Astronomical Union says that a planet "has cleared the neighborhood around its orbit." But many asteroids and comets cross Earth's orbit, so why is it still called a planet? Or, for that matter, why is even Jupiter a planet? The Trojan asteroids share Jupiter's orbit, so Jupiter hasn't "cleared" its neighborhood.

A The clearing is never perfect because asteroids, comets and meteoroids continue to stray into the neighborhoods of the planets. Yet the amount of this debris is negligible compared with each planet's mass. A more precise definition would say that a planet "dominates" its orbital zone. Jupiter's gravity controls the orbits of the Trojan asteroids. The IAU definition has the right idea, but its unqualified use of the word "cleared" has inadvertently caused some confusion.

Questions continued on page 40

instance, Earth is big enough that it eventually sweeps up or flings away any body that strays too close, such as a near-Earth asteroid. At the same time, Earth protects its moon from being swept up or scattered away. Each of the four giant planets rules over a sizable brood of orbiting satellites. Jupiter and Neptune also maintain their own families of asteroids and KBOs (called Trojans and Plutinos, respectively) in special orbits known as stable resonances, where an orbital synchrony prevents collisions with the planets.

These dynamical effects suggest a practical way to define a planet. That is, a planet is a body massive enough to dominate its orbital zone by flinging smaller bodies away, sweeping them up in direct collisions, or holding them in stable orbits. According to basic orbital physics, the likelihood that a massive body will deflect a smaller one from its neighborhood within the age of the solar system is roughly proportional to the square of its mass (which determines the gravitational reach of the massive body for a given amount of deflection) and inversely proportional to its orbital period (which governs the rate at which the encounters occur).

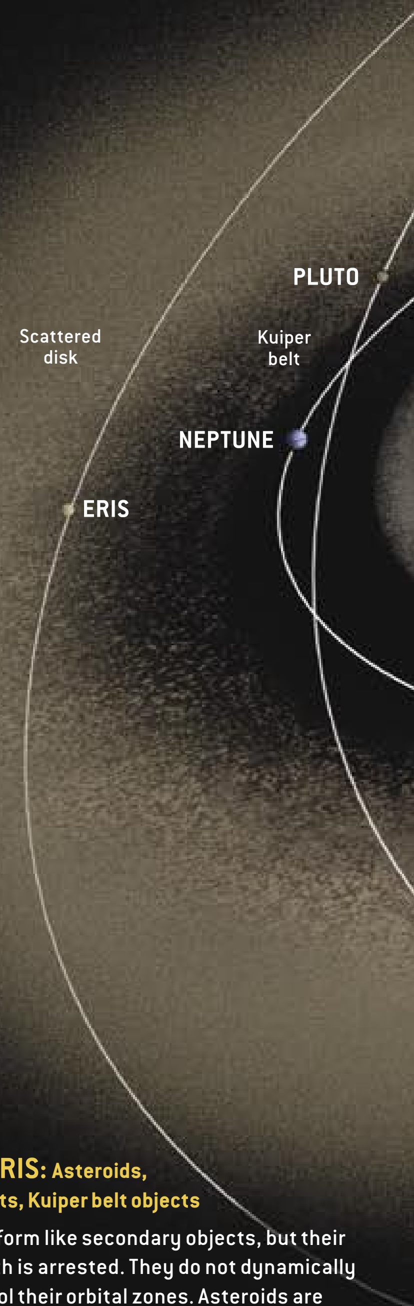
The eight planets from Mercury through Neptune are thousands of times more likely to sweep up or deflect small neighboring bodies than are even the largest asteroids and KBOs, which include Ceres, Pluto and Eris. Mercury and Mars by themselves are not massive enough to scatter away all the bodies in their vicinities. But Mercury is still large enough to sweep up most of the nearby small objects that cross its orbit, and Mars has sufficient gravitational influence to deflect passing objects into nearby unstable orbits, including some with periods exactly one-third or one-quarter that of Jupiter. The gravity of the giant planet then completes the task of ejecting those objects from the vicinity of Mars.

The ability of a body to clear its neighborhood depends on its dynamical context; it is not an intrinsic property of the body. Nevertheless, the large gap in dynamical power provides a clear way to

DON DIXON (*solar system*); LUCY READING-IKKANDA (*graph and orbits*)

THE "NEW" SOLAR SYSTEM

The planet definition approved by the International Astronomical Union is based on the observed architecture of the solar system, in which a small number of dominant bodies, the eight planets, have well-separated orbits, in contrast to the swarms of smaller asteroids, comets and Kuiper belt objects. Ceres and Pluto, once considered planets, are (along with Eris) swarm dwellers. Trojan asteroids share the orbit of Jupiter and are dynamically controlled by it. Centaurs are comets orbiting between Jupiter and Neptune.



TAXONOMY OF CELESTIAL BODIES

PRIMARY OBJECTS: Stars, brown dwarfs, sub-brown dwarfs

They form when an interstellar cloud collapses under its own gravity. Those with at least 80 times the mass of Jupiter undergo stable nuclear fusion of hydrogen and are called stars. Those in the range of 13 to 80 Jupiter masses undergo a brief period of nuclear fusion of deuterium, a rare isotope of hydrogen, and are called brown dwarfs. Less massive ones may be termed sub-brown dwarfs.

SECONDARY OBJECTS: Planets

They form when dust grains clump together in the rotating disk of material around a primary object. They undergo a period of runaway growth in which the larger ones sweep up most of the rest of the material. A planet that reaches a certain critical size can also pull in a thick envelope of gas.

TERTIARY OBJECTS: Satellites

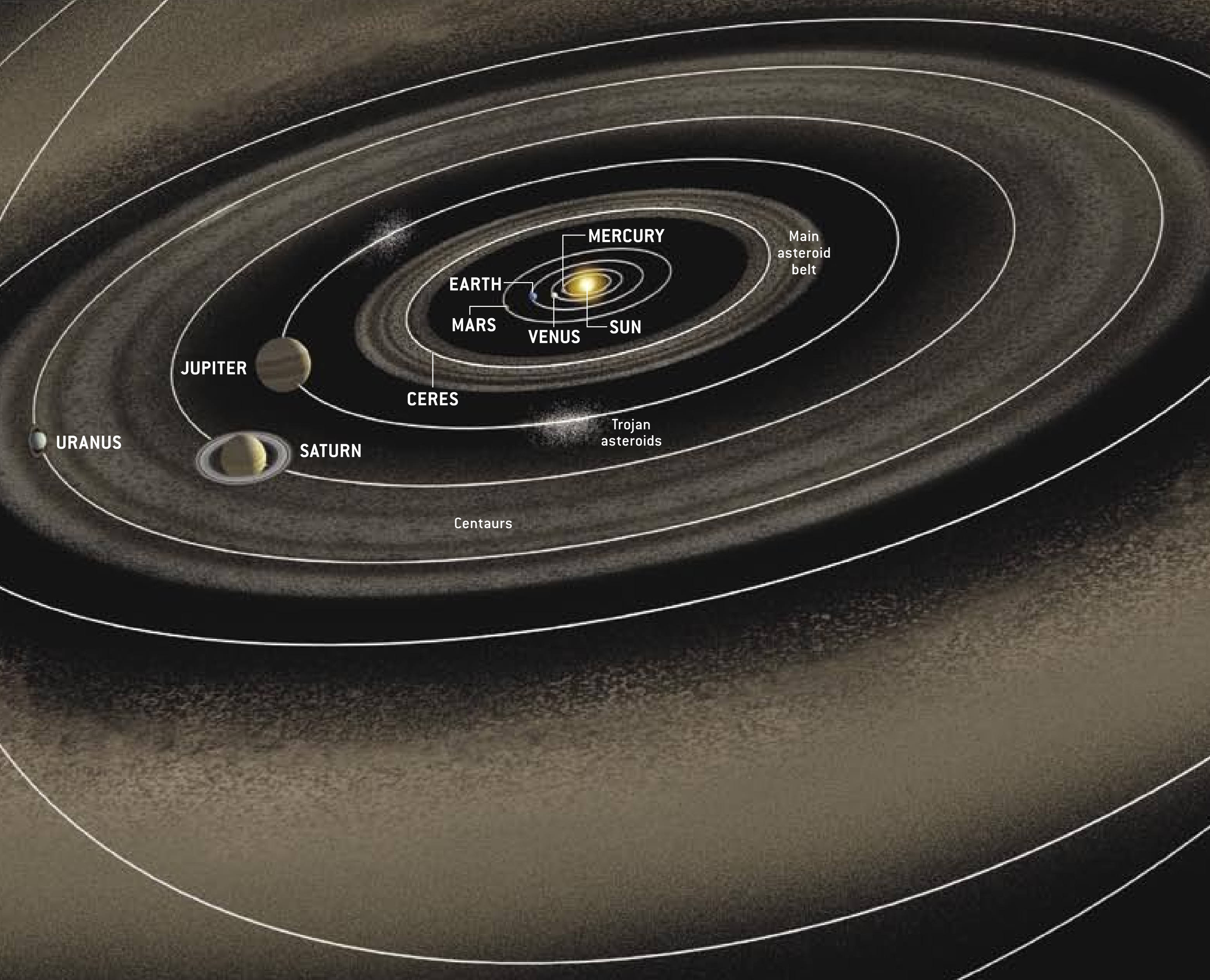
They orbit secondary objects, either having been formed in place or captured from independent orbits.

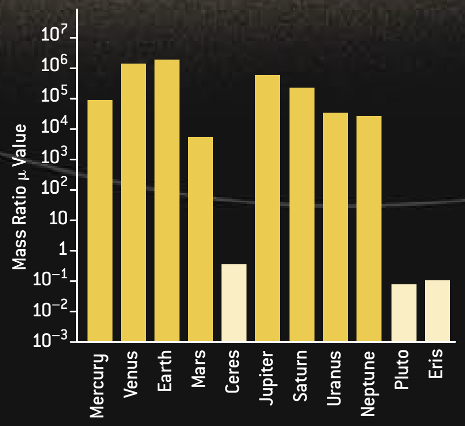
DEBRIS: Asteroids, comets, Kuiper belt objects

They form like secondary objects, but their growth is arrested. They do not dynamically control their orbital zones. Asteroids are small rocky worlds, most of which reside in a belt between the orbits of Mars and Jupiter. Kuiper belt objects are small icy bodies that orbit in a belt beyond Neptune; the belt appears to be the source of most periodic comets. The distinction between asteroids and comets is sometimes ambiguous: comets are typically more volatile-rich and form farther from the sun.

ROGUE PLANETS

They form as secondary objects but have been ejected to interstellar space. Simulations suggest that such objects may outnumber the stars in our galaxy. Observationally, though, they will be difficult to detect, let alone distinguish from free-floating sub-brown dwarfs that formed as primary objects.

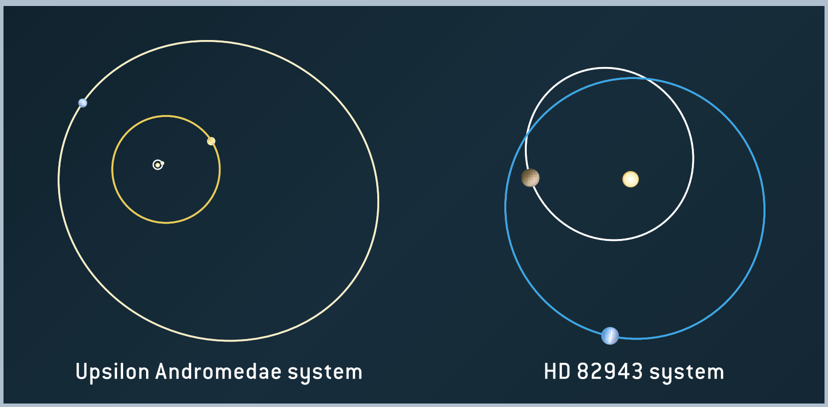




CLEAR DIVISION between planets (*gold*) and lesser bodies (*cream*) is evident in their mass ratio μ—the mass of a body divided by the total mass of all other bodies that share its orbital zone. All eight planets have a μ value of at least 5,000, whereas Pluto's is less than 1. A μ value of 100 serves as a convenient dividing line between planets and nonplanets in our solar system.

PLANETS ELSEWHERE IN THE GALAXY

ORBITAL DOMINANCE by a few bodies appears to be a property of other known planetary systems, too. In most, the planets' orbits do not overlap (*left*), so they are unable to collide. Even in those few cases where the orbits do overlap (*right*), an orbital synchrony prevents them from colliding.



MORE QUESTIONS

Q **Pluto's orbit crosses that of Neptune, so why is Neptune called a planet but not Pluto?**

A Neptune is more than 8,000 times as massive as Pluto and dominates its neighborhood gravitationally. Neptune long ago locked Pluto's orbit into a resonance with its own, making a collision between the two bodies impossible. Pluto is too small to dominate anything beyond its own satellites (one of which, Charon, is almost half as big as it is).

Q **Doesn't having a satellite qualify a celestial body to be a planet?**

A No. Many asteroids and Kuiper belt objects have satellites, but Mercury and Venus do not, and no one would deny that they are planets.

Q **If we discovered a Mars-size body in the outer Kuiper belt or even a Neptune-size body in the distant Oort cloud, would we call it a planet?**

A Not according to the new definition, because such a body would not dominate its neighborhood. We might need to coin a new term for it.

Q **Isn't it more practical to classify celestial bodies based only on their intrinsic features rather than on their orbital context?**

A Not necessarily. We already classify many objects as "moons" based on their orbital context. Some are as large as planets, and others are simply captured asteroids or comets, but we classify them by the shared dynamical characteristic of orbiting a planet.

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distinguish the planets from other bodies. We do not need to make an arbitrary distinction because, at least in our own solar system, nature does it for us.

Kings of Their Kingdoms

A CLOSELY RELATED criterion was proposed by astronomer Michael Brown of the California Institute of Technology in 2004. He defined a planet as "any body in the solar system that is more massive than the total mass of all of the other bodies in a similar orbit." To make this more precise, I have suggested replacing "similar orbit" with the concept of an orbital zone. Two bodies share such a zone if their orbits ever cross each other, if their orbital periods differ by less than a factor of 10, and if they are not in a stable resonance. To apply this definition, I undertook a census of the known small bodies that orbit the sun.

Earth, for example, shares its orbital zone with an estimated 1,000 asteroids larger than one kilometer in diameter, most of which are relatively recent arrivals from the main asteroid belt between Mars and Jupiter. They add up to less than 0.0001 percent of the mass of our planet. The ratio between the mass of a body and the mass of all other bodies that share its orbital zone can be abbreviated μ. For Earth, μ is about 1.7 million. In fact, Earth appears to have the highest μ value in the solar system. Jupiter is 318 times more massive but shares its orbital zone with a larger swarm of bodies. Mars has the lowest μ value for any of the planets (5,100), but even that is far greater than the value for Ceres (0.33) or Pluto (0.07) [*see box on preceding page*]. The result is striking: the planets are in a different league from the asteroids and KBOs, and Pluto is clearly a KBO.

Such arguments persuaded the IAU to define a planet in terms of "clearing" its orbital neighborhood. The IAU may need to amend the definition to specify what degree of clearing qualifies a body as a planet. I have suggested setting the cutoff at a μ value of 100. That is, a body in our solar system is a planet if it accounts for more than 99 percent of the mass in its orbital zone. But the exact value of this cutoff is not critical. Any value between about 10 and 1,000 would have the same effect.

A planet is thus a body that has swept up or scattered away most of the mass from its orbital zone. The clean division of bodies into planets and nonplanets reveals important aspects of the process that formed the solar system. All these bodies grew from a flattened disk of gas and dust orbiting the primordial sun. In the competition for the limited amount of raw material, some bodies won out. Their growth became self-reinforcing, so instead of a continuous spectrum of bodies of all sizes, the result was a single large body that dominated each orbital zone. The smaller bodies were swept up by the larger ones, ejected from the solar system or swallowed by the sun, and the survivors became the planets we see today. The asteroids and comets, including the KBOs, are the leftover debris.

Our solar system is now in the final cleanup phase of accretion. The asteroids have intersecting orbits that allow them to collide with one another and with the planets. The Kuiper belt is a remnant of the outer part of the original accretion disk, where the material was too sparse to form another planet. The planets of our solar system have orbits that do not intersect and so are unable to collide. As the dynamically dominant bodies, they must be few in number. If another planet tried to squeeze in between the existing ones, gravitational perturbations would eventually destabilize its orbit.

A similar situation appears to be true of other planetary systems as well. So far observers have found about 20 systems with more than one planet. In most, the planets have orbits that do not intersect, and in the three exceptions, the overlapping orbits appear to be resonant, allowing the planets to survive without colliding. All the known nonstellar companions of sunlike stars are massive enough to deflect nearby small bodies. They would probably qualify as planets by the criterion of dynamical dominance.

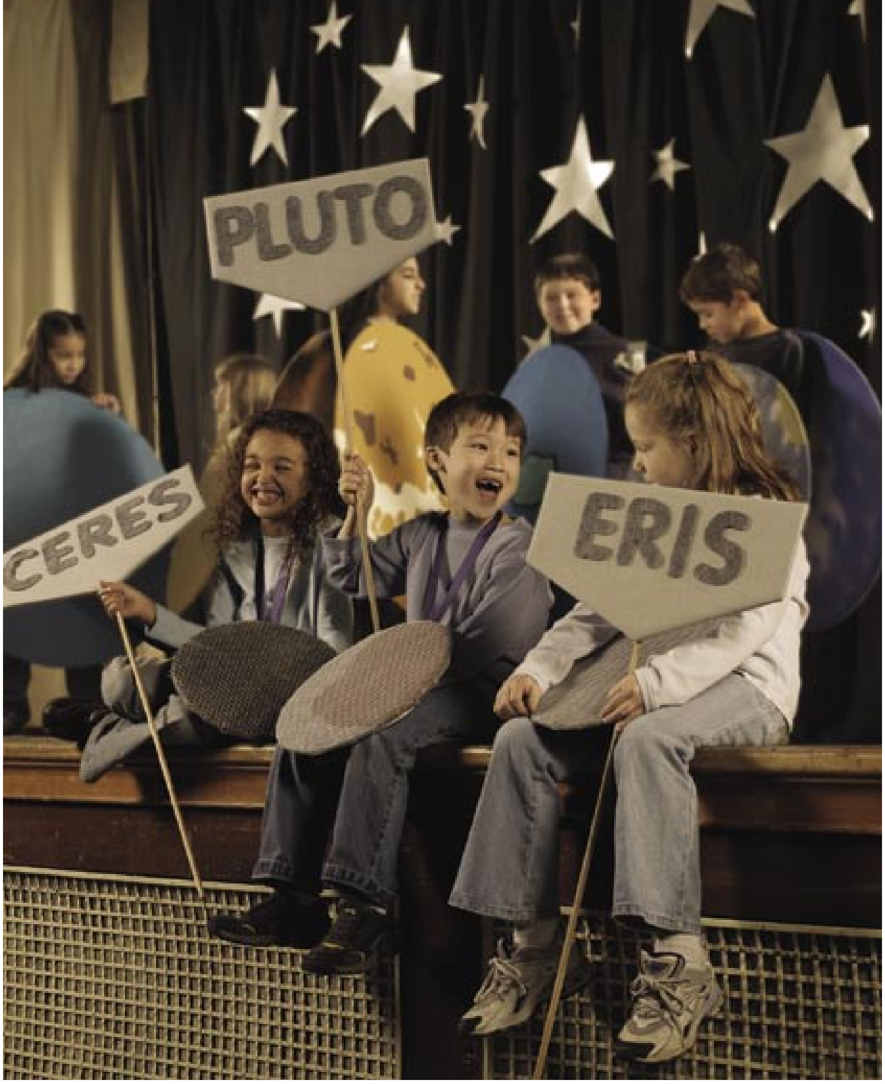
Endgame

A PLANET is, in effect, the end product of accretion from a disk around a star. This definition applies only to mature systems, such as ours, in which accretion has run effectively to completion. For younger systems, where accretion is still important, the largest bodies are not strictly planets but are called planetary embryos, and the smaller bodies are called planetesimals.

The IAU definition still includes roundness as a criterion for a planet, though strictly speaking, that is unnecessary. The orbital-clearance criterion already distinguishes planets from asteroids and comets. The definition also removes the need for an upper mass limit to distinguish planets from stars and brown dwarfs. The relatively rare brown dwarf companions orbiting close to stars can be classified as planets; unlike brown dwarfs in wider orbits, they are thought to have formed by disk accretion.

In short, the difference between planets and nonplanets is quantifiable, both in theory and by observation. All the planets in our solar system have enough mass to have swept up or scattered away most of the original planetesimals from their orbital zones. Today each planet contains at least 5,000 times more mass than all the debris in its vicinity. In contrast, the asteroids, comets and KBOs, including Pluto, live amid swarms of comparable bodies.

A prominent objection to any definition of this kind is the contention that astronomical objects should be classified only by their intrinsic properties, such as size, shape or composition, and not by their location or dynamical context. This argument overlooks the fact that astronomers classify all objects that orbit planets as "moons," although two of them are larger than the planet Mercury and many are captured asteroids and comets. Context and location are clearly important. In fact, distance from the sun determined that close-in bodies became small rocky planets and farther ones became giant planets rich in volatile ices and gases. The new definition distinguishes planets, which dynamically dominate a large volume of orbital space, from asteroids, KBOs and ejected planetary embryos, which do not. The eight planets are the dominant end products of disk accretion and differ recognizably from the vast populations of asteroids and KBOs.



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The historical definition of nine planets no doubt retains a strong sentimental attraction. But ad hoc definitions devised to grandfather in Pluto tend to conceal from the public the profound changes that have occurred since the early 1990s in our understanding of the origin and architecture of the solar system.

For 76 years, our schools taught that Pluto was a planet. Some argue that culture and tradition are sufficient grounds to leave it that way. But science cannot remain bound by the misconceptions of the past. To be useful, a scientific definition should be derived from, and draw attention to, the structure of the natural world. We can revise our definitions when necessary to reflect the better understanding that arises from new discoveries. The debate on the definition of a planet will provide educators with a textbook example to show how scientific concepts are not graven in stone but continue to evolve. SA

MORE TO EXPLORE

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