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No. 59 - Fall 2002

A Good Definition of the Word "Planet": Mission Impossible?

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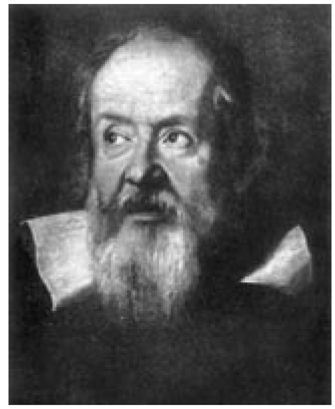
Ask anyone on the street to give an example of a planet, and they'll consider you a bit dim. Perhaps they'll answer with "Earth", or maybe one of the other obvious choices like Venus or Mars. If you ask "How about Pluto?" they may pause, having heard that there is a bit of a debate about that. If you ask, "What is the difference between planets and stars?", the number of people able to answer well drops dramatically, being a subset of the scientifically literate population (which we wish was much larger). Finally, if you ask "What is the exact scientific definition of 'planet'?", it turns out that *nobody* can answer it, because there really isn't one.

1) Looking (it) Up

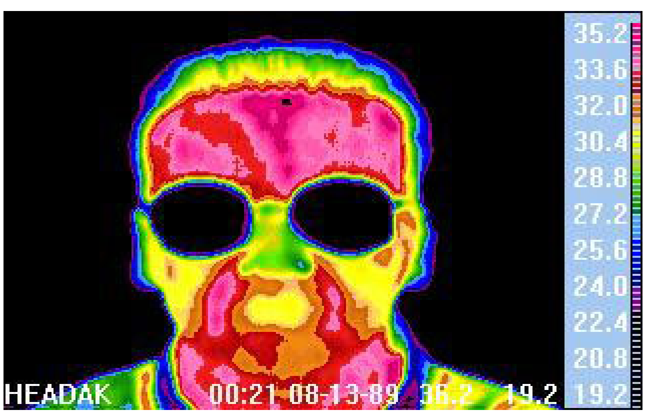
Of course, you can certainly look "planet" up in the dictionary (*have your students do this*). Mine says that a planet is "any heavenly body that shines by reflected sunlight and revolves about the Sun". It also notes that "planet" originally meant any heavenly body that moves with respect to the fixed stars, which included the Sun and Moon. The word itself means "wanderer" in Greek, and other cultures generally have words for "planet" with a similar meaning. So why isn't that good enough for us today? I suppose we can blame Copernicus and Galileo. The former taught us that basing everything on what we at Earth can see is a mistake, and the latter showed that using telescopes gives us far more information about the cosmos than our naked eyes. The discoveries since Galileo (and especially from the last decade) leave us with knowledge that renders the old definition of "planet" completely inadequate.

Nicholas Copernicus (1473-1543) published "On the Revolutions of the Heavenly Spheres" in the year of his death. In this work he proposed that the Earth is not the center of the Universe, but revolves around the Sun as do the other planets.

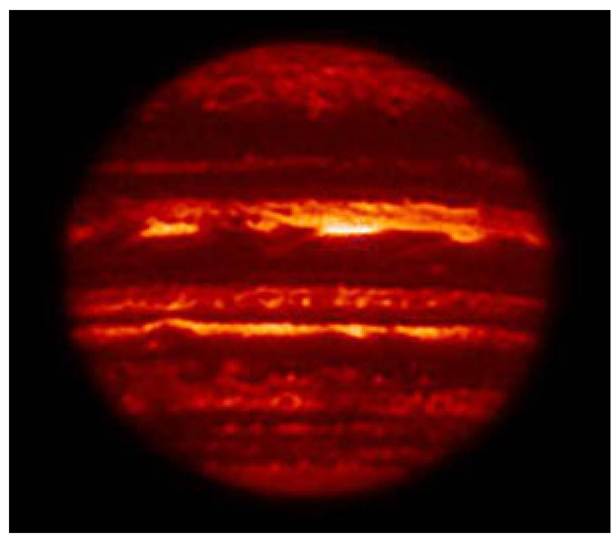


Galileo Galilei (1564-1642) used his telescope to make observations of the planets that supported the revolutionary ideas of Copernicus.

What's the problem? First of all, we now know that *all* heavenly bodies shine. It is just a matter of how brightly and with what kind of light. Anything with a temperature above absolute zero will emit light (more technically: electromagnetic radiation). Even *you* do! Objects at the temperature of people or the planets in our solar system do so primarily in the infrared (what we call "heat radiation": the stuff that night-vision goggles use). It is true that in visible light (the stuff your eye works with), the planets are much brighter from reflected sunlight than from their own luminosity. Actually, Jupiter emits more total radiation from its internal source than the amount of sunlight it reflects, but its internal radiation is mostly infrared. In any case, that is nothing fundamental, since it also depends on the distance of Jupiter from the Sun (*ask your students why?*). And it is certainly true that the Sun is vastly more luminous than any of the planets.



Red and Pink colors indicate regions where more heat is being emitted and yellow and green are cooler areas. Note that this person was wearing eye glasses when this picture was taken. Image courtesy Teletherm Infrared, Florida



The bright areas in this infrared image of Jupiter show regions where heat is escaping through gaps in the clouds. Jupiter has an internal heat source, and it emits twice as much heat as it receives from the Sun.

This argument may seem like a quibble, as does the second problem, which is caused by saying that planets must revolve about (orbit) the Sun. There was no problem with that until we began finding planets around other stars (in 1995). Now the count of extrasolar planets is roughly 100, and it will continue to increase rapidly in the foreseeable future. (See http://exoplanets.org/) Of course, one can generalize to "revolves about a star" rather than explicitly mentioning the Sun. We can thus fix the dictionary definition to something like "A planet is an object whose own luminosity is much fainter than the star which it orbits." This seems to improve the dictionary definition to be more in accord with current science. But alas, this is also completely inadequate!

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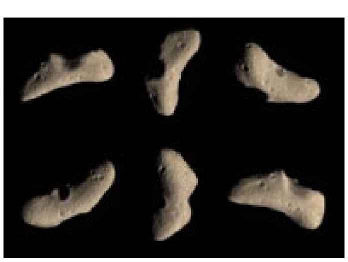
2) The Problem with Pluto

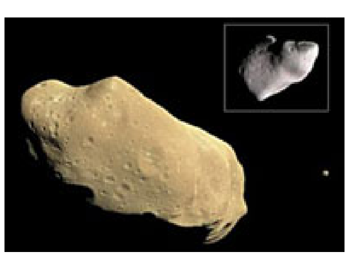
One of the remaining problems is illustrated by the "Pluto controversy". There has been a heated public discussion in the past few years about whether our ninth planet is really deserving of the name. Since Pluto orbits a star, and is *much* less luminous, it certainly satisfies the definition we have above. The problem is actually not with Pluto, but with a very large number of other bodies in our Solar System which also satisfy this definition, but which are not called planets. Perhaps the most notable of these is Ceres, the largest asteroid. Ceres was discovered in a deliberate search that was motivated by Bode's Law of planetary spacing (which we still don't understand, and doesn't really work with new discoveries). The planets known in the 18^{th} century all satisfied this law, but the fourth one seemed to be missing (between Mars and Jupiter). When Piazzi found an object in about the right orbit, it was hailed as the fourth planet. It was surprisingly small, but then Mercury is not much larger than our Moon anyway (and smaller than the largest moons of Jupiter and Saturn).

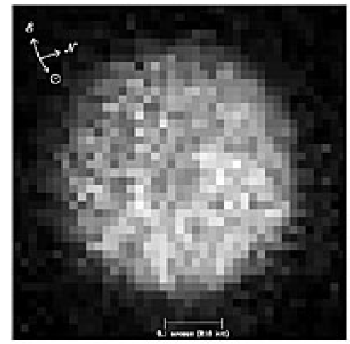
Bodes's Law		
Expected distance in AU	**Actual distance**	**Planet**
(0 + 4) /10 = 0.4	.4	Mercury
(3 + 4) /10 = 0.7	.7	Venus
(6 + 4) /10 = 1.0	1.0	Earth
(12 + 4) /10 = 1.6	1.52	Mars
(24 + 4) /10 = 2.8	2.1-3.5	asteroids
(48 + 4) /10 = 5.2	5.2	Jupiter
(96 + 4) /10 = 10.0	9.5	Saturn
(192 + 4) /10 = 19.6	19.2	Uranus
(384 + 4) /10 = 38.8	30.1	Neptune
(768 + 4) /10 = 78.0	39.6	Pluto

For more about this relationship, go to: http://ourworld.compuserve.com/homepages/jbstoneking/jbspage4.htm (A new window will open.)

The status of Ceres as the fourth planet came under attack only a couple of years later, when Vesta and Juno (smaller asteroids) were found in similar orbits. Herschel (who had previously been the only one to have found a planet, Uranus, by chance) began questioning whether any of them were really planets, since all the "proper" planets had their orbits to themselves. Such a concept, of course, had not previously been part of the understanding of "planet" (and didn't appear in our definition above). He won the day, however, as asteroids continued to be discovered. One suspects that this was largely because it just wouldn't do for our Solar System to have hundreds (or even thousands) of planets (*ask your students why not?*).





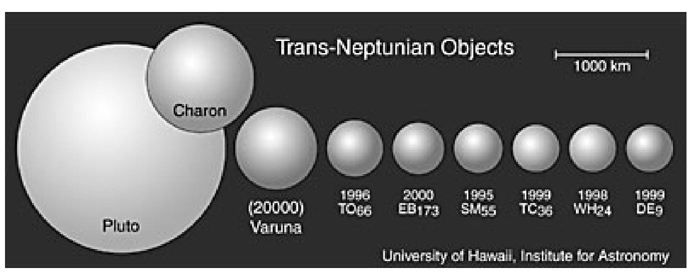


Asteroids (left to right) Eros, Ida (with its satellite Dactyl), and Gaspra have all been photographed by spacecraft and none of them is round. Ceres (far right) is the largest asteroid and is round.

Furthermore, all but the largest asteroids aren't even round -- they just look like rocks (some are admittedly extremely large rocks). That is because the planets are round due to the fact that their self-gravity is strong enough to overcome all material forces; the object must assume its most efficient shape (a sphere). Ceres is just over this limit (and so is round), while most asteroids are not massive enough. Comets (which also satisfy our definition above) are like icy asteroids. Comets tend not to have orbits like planets; their paths are not circular, may well cross several of the planets' orbits, and often have orbital planes that lie well out of the Solar System's plane (the ecliptic).

Pluto (like Ceres) was found as the result of a deliberate search. It was the same sort of search that had turned up Neptune. This relied on the observation that an outer planet had wobbles in its orbit which seemed to be caused by an undiscovered body further out. Careful calculation of Uranus' wobbles had led directly to the location of Neptune. Now Neptune also seemed to be wobbling, and a location for Pluto was calculated. It was very approximate, and Tombaugh (under Lowell's direction) had to search a big area before he found it. We now know that Pluto is far too small to cause any wobbles in Neptune (they weren't real), and Pluto's discovery is much more analogous to that of Ceres than Neptune. Like Ceres, Pluto is surprisingly small compared to the other planets, and further turned out to be much smaller than first thought. In fact, it is barely larger than Ceres, and smaller than many of the major moons. Its orbit is also somewhat comet-like (as is its composition), since its path is neither circular nor in the ecliptic. Nonetheless, for decades it was accepted as the ninth planet.

The complaints began when, as with Ceres earlier, other objects began to turn up in very "Pluto-like" orbits. These are all part of the Kuiper Belt -- the remains of the outer disk that originally formed the Solar System. Its presence had been predicted, but because the Kuiper Belt Objects (KBOs) are small and much further away than the asteroids, there was a gap of six decades rather than two years between the discovery of the largest example and smaller ones. Now, however, we know over 100 of these KBOs, and the next larger one is more than half Pluto's size. We may well find a larger KBO in the near future. A sizeable contingent of astronomers feels that if we are not going to call Ceres a planet, we really shouldn't call Pluto one either. The only real difference between them is that Pluto had a much longer grace period before its orbital companions were found. Alternatively, we should restore planethood to Ceres. Everyone agrees that we shouldn't call all objects orbiting the Sun "planets", so we have to have a reasonable way to exclude objects that are "too small" (or too low in mass). As with Godzilla, size matters, but where should we draw the line? Is "roundness" is a good criterion? (To find out more about these KBO's try this link: http://www.ifa.hawaii.edu/faculty/jewitt/kb.html)



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3) Planets and Brown Dwarfs

Other fundamental problems have arisen as a result of the discoveries outside our Solar System. All the extrasolar planets to date have been found by the "wobble method", which observes the line-of-sight velocity (Doppler shift) of the central star caused by a planet orbiting it. By its nature, this method is most sensitive to massive planets orbiting close to their stars. One difficulty is that it depends on the orientation of the orbit. If the orbit is face-on to us the method fails completely (no velocity towards or away from us). This has the effect that each inferred mass is actually a minimum possible mass. These minimal masses range from about Saturn's mass up to the brown dwarf limit. That means that some of the more massive extrasolar planets could actually be brown dwarfs (although the statistics of the finds suggest that most of them are not).

A brown dwarf is a "failed star" (rather than a planet), but what does that mean? How does one draw the line between the two? Here, astronomers diverge in their opinions as well. "Stars" are objects that shine by nuclear fusion. That is the source that powers hydrogen bombs, in which hydrogen nuclei are fused together to make helium nuclei, releasing energy. To shine, the star must have enough mass that its gravity crushes the star's center into an extremely hot dense state. The problem with brown dwarfs is that they collected enough mass to start fusion, but not enough to sustain it for long. Most of the time a brown dwarf's energy comes from the fact it begins slowly shrinking (the release of gravitational potential energy). This works in much the same way that dropping a weight on your foot works to hurt it (mass releases energy as it drops). This same energy source works for massive planets (like Jupiter) as well. These objects cannot generate nearly the power of the Sun, and as they become more compact the shrink rate is reduced, making them slowly fade out. There is a dividing line between objects with enough mass to ever have fusion, and those so small that they never do – at about 13 times the mass of Jupiter. Most astronomers are willing to draw the line between brown dwarfs and planets there. (For more information on brown dwarfs, try this link: http://oposite.stsci.edu/pubinfo/PR/2000/29/index.html)

The brown dwarfs are too dim to be seen in a visible-light image taken by the Hubble telescope's Wide Field and Planetary Camera 2 [picture at left]. This view also doesn't show the assemblage of infant stars seen in the near-infrared image. That's because the young stars are embedded in dense clouds of dust and gas. The Hubble telescope's near-infrared camera, the Near Infrared

Camera and Multi-Object Spectrometer, penetrated those clouds to capture a view of those objects. The brown dwarfs are the faintest objects in the image.

4) Born Into the Right Class?

Another possible difference between brown dwarfs and massive planets is how they are born. Our standard picture for the formation of a massive gas giant planet is that first a smaller planet forms, by the merging of even smaller bodies of rock or ice, called "planetesimals" (these are the size of the smaller asteroids, or comets). The growing planet must achieve above 10 times the mass of the Earth while the protoplanetary disk (out of which both star and planets form) still contains its primordial gas (hydrogen and helium). If so, the planet can attract this gas and quickly grow into a gas giant. It is unclear if there is a limit to how large it can grow thereafter. Of course, if it grows past 13 Jupiter masses it can begin fusion, and become a brown dwarf companion to the star. But some astronomers would say it is still a planet because of its mode of birth. They would base the fundamental definition on the mode of formation: a planet is built from planetesimals.

Brown dwarf companions, though, have usually been thought of as forming in the same way stellar companions do (and these are quite common). They do not go to the trouble of building up from small objects. A large denser region of gas collapses under its own weight, and directly makes the object. We see that stellar companions (which we think form this way) often do not have circular orbits, while circular orbits prevail in our Solar System. That had been interpreted as a natural outcome of the planetesimal merger scenario above. It was therefore a surprise to find that most of the extrasolar planets have non-circular orbits. A few iconoclasts have even suggested that therefore the extrasolar planets are misnamed. In fact, our formation theories are nowhere close to being sure about what the mass limits for either mode of formation (direct or merger) are, nor whether circular orbits should result. Furthermore, the orbits we see today may well not be the original ones. Both the remaining disk and any other reasonably massive planets in the system can alter them during the early history.

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5) Runts and Runaways

Indeed, one alteration of orbits can be the outright ejection of a planet. When several big planets are orbiting a star under each other's influence, the system is inherently unstable. The almost inevitable result is that the smallest body will be ejected from the system. We would see it as an isolated object smaller (less massive) than a brown dwarf. Such objects have indeed been found in some young star clusters. The problem is, we are not sure whether such small objects can also just form by themselves, without ever being in orbit around a star. Originally theorists claimed this was not possible, but as more details were added, they retreated. We know of no good reason why the smallest objects with fusion should have the same mass as the smallest objects that can form by themselves. At the moment it seems more likely that the discoveries are not true ejected planets (but it is very hard to be sure).

A controversy therefore arose when they were dubbed "free-floating planets" by some of the discoverers. The question is: if the object was never in orbit around a star, can we call it a planet? Some astronomers say that if it never had fusion then it clearly isn't a star (failed or otherwise). Since the free-floating objects have the same mass as some of the accepted extrasolar planets, they should be called planets too. Others say that planets can only form and be found around stars (leaving aside the problem of ejection), so if the new objects formed in isolation they should be called "sub-brown dwarfs" or "grey dwarfs", but certainly not "planets".

The latest computer simulations of star formation only further confuse the issue. They show that in the formation of a cluster of stars, fetal objects are often interacting with each other, forming loose alliances, then being ejected from the group while formation is still in progress. Brown dwarfs sometimes form by themselves. Sometimes they are part of a multiple star system in the process of formation, when they are suddenly tossed out (robbing them of their "rightful" supply of gas). The same could be true of objects in the planetary mass range, in which case it is hard to say whether they formed in orbit around a star or not. (For more information on these computer models, try this link: http://www.astro.ex.ac.uk/people/mbate/Research/pr.html)

6) Mission Definition

By now you should be at least as confused as professional astronomers are. What seemed like an easy question ("what is a planet?") has become a morass. Still, the word is in very common use, and it would be nice to know what we are talking about. A final definition should be acceptable to both scientists and the lay public. *Your mission, should you choose to accept it, is to concoct such a definition.* There are three arenas from which the definition could spring. They are not necessarily compatible with each other, and one or more may not be necessary. These are 1) the **characteristics** of the objects themselves; 2) the **circumstances** in which they are found; and 3) their **cosmogony** (how they form).

I here suggest a few properties that the definition perhaps should satisfy, but you are free to add to and subtract from this list at will. A good way to start is probably to settle on the list for yourself. My suggestions (in no particular order) are that a definition should 1) be **physical**: give some fundamental properties of the object; 2) be **observable**: depend on measurements that are feasible to accomplish; 3) be **succinct** and clear, with little ambiguity; 4) be **general** beyond current observations: allow room for new discoveries; 5) have **well-defined limits**: except right at these limits it should be easy to place an object inside or outside the category; and 6) be **easily understood** by the public but satisfactory to scientists.

The International Astronomical Union (the only body empowered to make an "official" definition), has found the task problematic so far. Nature, of course, cares nothing about classification, and the truth is that there is a continuum of characteristics, circumstances, and probably cosmogonies to the objects out there. This article contains the beginnings of many of the relevant issues. Have the students extract them (and perhaps augment them with their research), and organize them so to aid in carrying out the mission. Can they bring clarity to the classification and cut through the confusion? Can they make a definition for "planet" that other students will like and understand, and that teachers and astronomers will also find compelling? It should at least be fun and informative to try.

I don't think this mission is impossible, and will suggest a definition in a future article in *Mercury.* Or you can get a preview at my website (http://astro.berkeley.edu/~basri/whatsaplanet.htm) after you have finished your own thought process. This document will not self-destruct anytime soon, and you are free to spread it around. Good luck!