VARIOUS DEFINITIONS OF A PLANET*

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The term planet currently does not have a unanimous agreement upon definition. The most widely accepted criteria proposed by the International Astronomical Union (IAU) in 2006 are not undisputable. Perhaps the most controversial topic is the idea of determining the planetary status of an object not only by its own physical properties like mass or roundness, but also by its orbital properties, such as the type of its orbital parent and the object gravitational dominance. It is also difficult to draw the exact boundaries of all these properties. Another issue is developing a definition that is universal and useful, and that can be further developed for objects that have not yet been discovered or for which there is only a limited amount of data available, such as some Trans-Neptunian Objects (TNOs) or extrasolar bodies. In the wake of an era of discovery when new Solar System objects and exoplanets are being detected, it may be beneficial or even necessary to reconsider and possibly redefine what exactly a planet is.

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1. The history of "planet"

The term planet has been in use since antiquity and, expectedly, has evolved and changed its meaning as new discoveries were made throughout the ages. Knowing its history, which was described in detail by Metzger *et al.* [1], could help with deciding what this term should refer to, especially since almost six thousand exoplanets have been detected so far. Originally, the phrase "planet", meaning "wanderer" in Greek, was used to describe a type of celestial object that moved in relation to fixed, unmoving stars. This definition included the Sun, the Moon, Mercury, Venus, Mars, Jupiter, and Saturn. A major change to the term came with the spread of the heliocentric model during the Copernican Revolution, when the Sun was deemed not to be a planet. At the same time, Earth was added to the list of planets since it revolved around the system central star. The Moon and satellites of other worlds were still referred to as planets. To distinguish them from

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objects that orbited the Sun without revolving around another object at the same time, the term “secondary planet” was proposed, which was a synonym of “moon” and “satellite”. The idea of excluding moons from the category of planets originated in the 19^{th} century, and it was not until the 1960s that the scientific community regained interest in calling the large, round moons “planets”. Stern and Levison [2] proposed a geophysical definition, based on intrinsic geophysical properties, as opposed to the external orbital properties. They described a planetary object as a body that has a mass low enough to never have undergone nuclear fusion and which is massive enough for its shape to be determined primarily by gravity. Currently, the most widely accepted criteria, are those proposed in 2006 by IAU Resolution B5 «Definition of a Planet in the Solar System» [3]. This astronomical definition states that a planet is a celestial body that is in orbit around the Sun, has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium, and has cleared the neighbourhood around its orbit. As this definition can only be used for the Solar System objects, the IAU has also created separate criteria for planets outside of our system — the so called “exoplanets”. These objects are in orbit of a star, stellar remnant or a brown dwarf, and did not and will not undergo deuterium fusion. Their mass ratio with the central object is determined to be below the L4/L5 instability, and their lower mass requirements are the same as those for the planets in the Solar System.

2. Orbital parent

Problems can be found within all the definitions. Limiting the IAU definition of planets only to the Solar System creates the need for separate requirements for exoplanets. While it would be beneficial to create a more universal definition, it is a rather difficult task, considering the relative proximity of Solar System objects when compared to extrasolar ones. Some objects within our system also remain a mystery. There are numerous TNOs with an unresolved status. Some of them can be classified as possible dwarf planets [4]. At least unifying the orbital parent requirement is simple since the Sun already falls within the “star, stellar remnant or brown dwarf” category. However, it is disputable whether a planet should be required to orbit anything at all. The IAU has deemed an object location and gravitational bonds to be extremely important in determining its planethood. Nevertheless, when deciding whether a body is a star, its location is of no consequence and only the object intrinsic properties are. There exist free-floating planetary-mass objects that are not bound to any parent objects, such as stars or planets [5]. It can be assumed that these free-floating objects are planets and they are called rogue planets. One could argue that by excluding such rogue planets, the definition is more traditional and adheres to the views of the Copernican Revolution, in which revolving around the Sun (and analogously, other stars) is the key element. However, the requirement that an orbital parent must be of a certain type excludes natural satellites of planets from being planets. Numerous moons in our system would be considered planets if only they were ejected from their orbit and achieved a stable orbit around the Sun. Two of them — Ganymede and Titan — have radii larger than that of Mercury. An analogy could be drawn that in binary star systems in which the barycentre is inside of the more massive component, the smaller companion is still a star, and not a different kind of object. It is of course important to distinguish moons from planets. The question is rather where to make that distinction [6]. Should natural satellites be excluded entirely from planets, or should that distinction be made on a lower level, as had been suggested in the past with "secondary planets" being a type of planet? Perhaps the synonymy of terms "satellite" and "moon" could be used here, and a moon could be defined as a satellite of a planet that is also a planet. Such a solution would result in a drastic change in the number of moons in our system. Objects orbiting stellar remnants, such as: pulsars, black holes, neutron stars, white dwarfs, create a difficulty in giving a name to each of them. In literature, some of them are already present. The first exoplanet discovered by Wolszczan and Frail is an example of a pulsar planet [7]. Planets orbiting black holes have been proposed to bear the name "blanet" [8]. Is it better to broaden the spectrum of possible orbital parents or narrow it down, for example by excluding brown dwarfs and stellar remnants? It could be argued that the second approach adheres more to the original concept, where planets were supposed to orbit the Sun. And like moons are a special non-planetary case, so would be pulsar planets, blanets, brown dwarf planets, *etc.*

3. Sharing orbits

The third IAU requirement, regarding the clearing of the neighbourhood is also problematic. First, how exactly to interpret its meaning, *i.e.* how much clearing does an object have to do? Clearly, possessing natural satellites or rings does not disqualify a body. Neither does matter located in an object Lagrange points, such as Jupiter trojans or Earth Kordylewski clouds. Stern and Levison [2] addressed those instances. They described a gravitationally dominant body that distinctly dictates the trajectories of smaller objects in its neighbourhood by ejecting them or trapping them in resonances or satellite orbits. Another way to address the issue, suggested by Brown [9], would be to discern planets as objects more massive than the total mass of all of the other bodies in orbit. This definition, however, has been proposed for the Solar System only, and would be difficult to implement in extrasolar cases. It is clear then that a more precise wording of the orbit-clearing criterion would be beneficial in the removal of all uncertainties. A way to make this requirement quantitative was proposed by Margot [10], who developed a formula to ensure the ability of an object to clear debris from its vicinity in the host star lifetime on the main sequence (for main sequence stars). Using parameters, such as the mass and orbital time of the object, which are known even for exoplanets, makes this criterion very useful. Yet, is this requirement necessary? If Earth was due to some gravitational perturbations moved into the asteroid belt, it would cease to be a planet until it ejected smaller bodies. Such an approach seems counterintuitive and time-dependent [2]. Unlike a star, an object can become or cease being a planet due to some external event rather than only by its own evolution.

The introduction of the third criterion by the IAU also created a new class of objects — the "dwarf planets". This term is quite unfortunate, as although they have the word "planet" in their name, these objects are not planets at all. It is yet another discrepancy between classifying stars and planets. Giant stars and dwarf stars are still (generally) stars. Giant planets are planets, but dwarf planets are not. Again, maybe like with moons, it could be worth considering defining dwarf planets as a type of planet. Additionally, there seem to be special cases regarding a planet that shares an orbit with another object. The concept of a multiple (binary or even tertiary, *etc.*) planet, where the barycentre of both objects is outside all of them, needs to be considered. This concept could be completely omitted by simply always calling the smaller object a satellite, however, this would probably create a grey area in cases where both objects are extremely similar in mass. Another, hypothetical case is a planet sharing an orbit with another object in one of its Lagrange points — a trojan planet. As there are examples of trojan natural satellites in the Saturn system, this should be at least considered. There are also many other hypothetical cases in which classification of a body as a type of planet or a different object could be not straightforward.

4. Intrinsic properties

Determining the object nature based solely on geophysical properties is also not without difficulty. Establishing the upper-mass limit of planets is perhaps the simpler issue. Astronomers [3] and geophysicists [2] agree that a planet cannot sustain a thermonuclear reaction. This determines the upper mass limit of a planet to be 13 masses of Jupiter if it has the metallicity of the Sun [11]. It would be more accurate to derive such a limit for each object, considering its metallicity as well as helium and deuterium abundance [12], but as this could be difficult for extrasolar objects, keeping the fixed value of the mass parameter might be the better choice.

The lower limit separating planets from smaller objects is their nearly spherical shape [3]. This omits of course minute discrepancies like polar flattening due to rotation. This roundness requirement is achieved by the body mass being large enough to overcome the rigid body forces and reach hydrostatic equilibrium. However, reaching the hydrostatic equilibrium is not necessary. For example, the planet Mercury is not in hydrostatic equilibrium [13]. The roundness requirement would be met by objects that have a radius greater than their "potato radius" — the value of a radius under which the object does not collapse under its own gravity and has an irregular shape [14]. This potato radius depends on the object density and thus the material of which the object is composed. For example, the size of the object needed to reach the planetary shape is much smaller for icy bodies than for rocky bodies. However, determining the properties of relatively small objects on the far reaches of the Solar System is very difficult. Drawing the boundary at some abstract but round radius value could be therefore tempting and convenient, but it would not necessarily reflect the actual characteristics of a body. It has been also proposed to entirely omit this lower-mass requirement, seeing that an object ability to gravitationally dominate their neighbourhood should already suffice in guaranteeing the body spherical shape [10]. Although, the applicability of such a solution could be dubious if moons, dwarf planets, and rogue planets were supposed to be planets.

5. Conclusion

The matter of defining a planet is clearly not yet entirely solved and needs to be discussed at length among specialists from various fields of research. The problem has complex roots, but the key factors are incomplete understanding of what astronomical objects are, and using different approaches in determining the planetary status of an object. It is of course possible to have different definitions in astronomy and geophysics, but the question is if such a solution is a useful one. It is probably possible to construct a unified definition, and a better one than that devised by IAU, but the most restricting factor is perhaps the limited data available on distant objects. As our knowledge increases, it may become easier to draw the boundaries. Then again, it is also possible that new discoveries will raise even more questions. Therefore, it may be beneficial to bring as much order as possible to our existing naming systems as soon as possible. Besides deciding which criteria to use, it is important to decide at what level they should be drawn. Should they only differentiate planets from other objects or also individual types of planets from each other?

A glaring issue which seems to need to be addressed is the discrepancy between naming planets and naming stars. Some common ground appears to exist, with many definitions agreeing that a planet needs to at least be characterised by its inability to fuse deuterium and by its almost spherical shape. Restricting the requirements to these two, effectively leaning more towards the geophysical view, would arguably create a more orderly system, quite analogous to defining stars. Keeping the upper limit at deuterium-burning mass would be useful in extrasolar cases. Whether that value should be fixed or dependent, for example, on the object metallicity, should be determined by the ability to measure those parameters. The lower limit of a planet also needs to be quantitative, either by setting it at the value of a potato radius, if it can be calculated for extrasolar bodies, or by one of the proposed gravitational dominance calculations, if they do in fact guarantee the object sphericity. Using the second solution would not be possible for cases, such as: rogue planets, dwarf planets, or binary planets. Then, all orbital properties, such as the parent object, could be used to differentiate between planet types. However, any official change must be thought out thoroughly, as no solution will likely satisfy all researchers. Then again, it is important to remember that all boundaries and criteria, no matter how official, are just an artificial attempt at trying to organise the complexities of nature for our human understanding.

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