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Invited review

THE DEFINITION OF PLANET: A DYNAMICIST'S POINT OF VIEW

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SUMMARY: It is here argued that the problem of a meaningful defininition of "planet" is best addressed on a dynamical basis; we show that in this way it is possible to obtain a planet definition that is both unambiguous and useful.

Key words. Planets and satellites: general

1. INTRODUCTION

From time immemorial mankind has noted that planets move appreciably, compared to fixed stars, thus making a distinction between these two types of celestial bodies.

In fact, the problem of planetary motions is, together with that of the lunar motion (see, e.g. Gutzwiller 1998), the oldest problem of astronomy, and thus of science. It was formulated by Newton[1] (1730, see also Figure 1), who posed the question of the long term stability of the planetary system. The underlying concept of a small number of massive bodies going around a central, more massive one in quasi-circular, quasi-coplanar paths that encompass a region of space far larger than the physical sizes of the bodies involved, has become so entrenched in scientific thinking that many quantum mechanics teachers have a hard time in trying to avoid that their students apply that concept too literally to the structure of atoms.

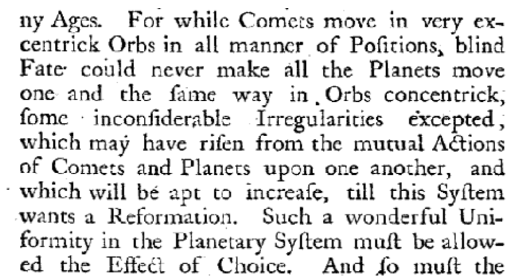
ny Ages. For while Comets move in very excentrick Orbs in all manner of Poſitions, blind Fate could never make all the Planets move one and the ſame way in Orbs concentrick, ſome inconſiderable Irregularities excepted, which may have riſen from the mutual Actions of Comets and Planets upon one another, and which will be apt to increaſe, till this Syſtem wants a Reformation. Such a wonderful Uniformity in the Planetary Syſtem muſt be allowed the Effect of Choice. And ſo muſt the

Fig. 1. *The excerpt from Newton (1730) in which the roots of the problem of the stability of planetary orbits may be found.*

[1] Newton's words: "For while Comets move in very excentrick Orbs in all manner of Positions, blind Fate could never make all Planets move one and the same way in Orbs concentrick, some inconsiderable Irregularities excepted, which may have risen from the mutual actions of Comets and Planets upon one another, and which will be apt to increase, till this System wants a Reformation. Such a wonderful Uniformity in the Planetary System must be allowed the Effect of Choice"; note how Newton emphasizes the "Planetary System", rather than speaking of individual planets.

Newton's question came not long after one of the most profound revolutions in scientific thinking, the transition from the Tolemaic to the Copernican system; as a consequence of that transition, the first significant change of the number of known planets took place, with the Moon being recognized for what it is, a satellite of the Earth; previously, in geocentric conceptions of the universe, it was naturally considered to be a planet not dissimilar from the others.

At other times the discovery of a new celestial body has posed the question of whether the number of planets should be revised; two of these cases, the accidental discoveries of Uranus and of Ceres, took place within one generation.

The former took place at the time of the great systematization of our understanding of celestial motions due to Lagrange and Laplace; for the first time, an accurate mathematical description of how planets affected the orbits of each other became available.

The latter case, the discovery of Ceres, is tied to two very important advances, both due to Gauss: the algorithm to compute an orbit from a small number of observations and especially the least squares method, both invented to recover Ceres. That the newly discovered body was not a planet became clear quickly, because of the discoveries of Pallas and Vesta within the next few years.

The discovery of Neptune, almost half a century later, represented a real triumph for Celestial Mechanics: the presence of the planet was inferred from its perturbations on the orbit of Uranus by two astronomers, LeVerrier and Adams, working independently and arriving at similar results, with the planet being discovered very near to where LeVerrier had predicted it to be.

Coming to more recent times, it is now acknowledged that, when Pluto was discovered, as a consequence of the dedication and skill of Tombaugh, an unfortunate series of circumstances led to the attribution, in good faith, of the status of planet to a body that actually should have been considered the first of a new population of small solar system bodies. What led to the misunderstanding was the fact that it was found at about the right longitude of the (then presumed) perturber of Neptune, so that to Pluto was quickly attributed a mass of the order of that of the Earth.

That this was questionable, and could have induced to a gross overestimate of Pluto planetary status, was already warned by Leuschner on page 213 of his 1932 paper (Leuschner 1932): "What shall we conclude on the other hand if the future shows that Pluto, as is the case with comets, has no mass sufficiently appreciable to affect other bodies of the solar system? It may then have to pass into the class of objects known as minor planets...".

However, it took almost half a century before the discovery of its satellite allowed to find the real mass of Pluto, and more than another decade before the discovery of 1992 QB_1, after which it started to become clear that in the trans-neptunian region of the solar system a real planet had failed to form, just as in the main asteroid belt.

This ensuing discovery of Eris, a transneptunian body larger and more massive than Pluto, caused the International Astronomical Union (IAU) to consider in a more formal way the definition of planet. As a consequence of a hot debate, taking place before and at the 26$^{\text{th}}$ IAU General Assembly, held in Prague in August 2006, a resolution was adopted, in which a definition of "planet" is given.

2. THE IAU RESOLUTION

IAU Resolution B5, adopted at the 26$^{\text{th}}$ IAU General Assembly, states:

A planet is a celestial body that

(a) *is in orbit around the Sun,*

(b) *has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and*

(c) *has cleared the neighbourhood around its orbit.*

The Resolution adds, in a note, that *The eight planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune*, a straightforward consequence of the definition just seen.

This definition relies on a set of conditions whose nature may be described as dynamical (condition *a*), physical (condition *b*), and evolutionary (condition *c*); this is due to the way in which it was arrived at, through a series of compromises among competing views.

To the present author, this mixture of arguments of different nature seems unnecessary, and obscures, rather than clarify, the issue; in the following, a definition based solely on dynamical arguments is given, and is shown to be adequate to the purpose.

3. THINGS THAT SHOULD MATTER

The main issues that a meaningful description of planet should address are essentially the following three:

1. their mutual distances should not allow close encounters or collisions;
2. they should detectably perturb each other, as well as perturb the motion of the star they orbit;
3. they should be able to perturb out of the way any body that would possibly encounter them.

To put the above points on quantitative grounds, Table 1 shows a number of relevant quantities for the IAU-sanctioned solar system planets; its columns contain:

1. the name;
2. the orbital semimajor axis a, in AU;
3. the orbital eccentricity e;
4. the approximate minimum distance $d_{\min} = a(1-e) - a_i(1+e_i)$, in AU, from the immediately interior planet; e_i is the orbital eccentricity of the immediately interior planet;
5. d_1, the same as above, but in units of the radius of the planet at the current row;
6. d_2, the approximate orbital minimum distance from the immediately exterior planet in units of the radius of the planet at the current row;

Table 1. Relevant quantities for the eight planets; for a detailed explanation, see the text.

Body	a	e	$d_{\min}$	d_1	d_2	$m_\odot/m$	ϵ^{23}	ϵ_{32}
Mercury	0.39	0.21			$2 \cdot 10^4$	$6.0 \cdot 10^6$	$5 \cdot 10^{-8}$	
Venus	0.72	0.01	0.25	$6 \cdot 10^3$	$6 \cdot 10^3$	$4.1 \cdot 10^5$	$1 \cdot 10^{-6}$	$4 \cdot 10^{-7}$
Earth	1.00	0.02	0.26	$6 \cdot 10^3$	$9 \cdot 10^3$	$3.3 \cdot 10^5$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$
Mars	1.52	0.09	0.36	$2 \cdot 10^4$	$1 \cdot 10^5$	$3.1 \cdot 10^6$	$3 \cdot 10^{-8}$	$9 \cdot 10^{-8}$
Jupiter	5.20	0.05	3.29	$7 \cdot 10^3$	$8 \cdot 10^3$	$1.0 \cdot 10^3$	$3 \cdot 10^{-4}$	$2 \cdot 10^{-5}$
Saturn	9.54	0.05	3.56	$9 \cdot 10^3$	$2 \cdot 10^4$	$3.5 \cdot 10^3$	$7 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
Uranus	19.2	0.05	8.23	$5 \cdot 10^4$	$6 \cdot 10^4$	$2.3 \cdot 10^4$	$2 \cdot 10^{-5}$	$5 \cdot 10^{-6}$
Neptune	30.1	0.01	9.71	$6 \cdot 10^4$		$1.9 \cdot 10^4$		$1 \cdot 10^{-5}$

7. $m_\odot/m$, the inverse mass of the planet in units of the mass of the Sun;
8. the quantity $\epsilon^{23} = (m_\odot m)/(m_\odot + m)^2 \cdot (a/a_e)^2$, where $m_\odot$ is the mass of the Sun, m, a are the mass and semimajor axis of the planet under consideration, and a_e is the semimajor axis of the planet orbiting in the immediately exterior orbit; the dimensionless parameter ϵ^{23}, introduced by Walker et al. (1980), gives a quantitative measure of the perturbation by the planet under consideration on the one in the immediately exterior orbit;
9. the quantity $\epsilon_{32} = m/(m_\odot + m_i) \cdot (a_i/a)^3$, where m_i, a_i are the mass and the orbital semimajor axis of the planet in the immediately interior orbit; the dimensionless parameter ϵ_{32}, also introduced by Walker et al. (1980), gives a quantitative measure of the perturbation by the planet under consideration on the one in the immediately interior orbit.

Let us discuss the three issues in turn hereafter.

3.1. Mutual distances

Columns 4, 5 and 6 of Table 1 quantitatively characterize the spacings among planetary orbits; when expressed in AU these spacings are not particularly telling but, when expressed in units of the radii of neighbouring planets, as done in columns 5 and 6, one immediately notices that they are counted at least in the thousands (if not much more), vividly illustrating the basic emptiness of interplanetary space and the unlikelihood of close encounters.

3.2. Mutual perturbations

That there must be a minimum threshold level of mutual perturbations between neighbouring planets is necessary in order to avoid having a grain of sand going around the Sun be considered a planet; it is after Newton that the idea of the mutual disturbances of the planets has become part of the picture, as it is clearly implied by his question about the long term stability of the solar system.

Columns 8 and 9 of Table 1, as well as Fig. 2, characterize solar system planets from this point of view. Especially in the Figure it is evident how the mutual perturbations between adjacent terrestrial planets are smaller than those between adjacent giant planets; however, within both of these groups the spread of the values is confined within less than two orders of magnitude.

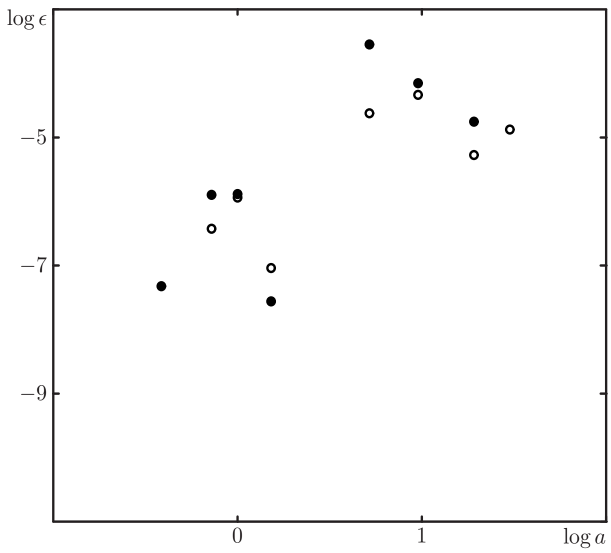

Fig. 2. *The values of* $\log \epsilon^{23}$ *(full dots) and of* $\log \epsilon_{32}$ *(empty circles) plotted against* $\log a$ *for the eight solar system planets.*

The situation would drastically change if we were to introduce Ceres, Pluto and Eris, three of the largest bodies not qualifying for planetary status according to the IAU (they are in fact considered "dwarf planets", see Tancredi and Favre 2008): Table 2 gives the same quantities as Table 1 for the triplets of neighbouring bodies Mars-Ceres-Jupiter and Neptune-Pluto-Eris, while Fig. 3. gives a global view of the mutual perturbations for the planetary system plus the three additional bodies.

While from the point of view of mutual distances there would be no problem with the addition of Ceres, Pluto is prevented from encountering Neptune only by its 2/3 mean motion resonance with that planet, and nothing prevents encounters between Eris and Pluto.

Table 2. Same as Table 1 for some dwarf planets.

Body	a	e	$d_{\min}$	d_1	d_2	$m_\odot/m$	ϵ^{23}	ϵ_{32}
Mars	1.52	0.09			$4 \cdot 10^4$	$3.1 \cdot 10^6$	$1 \cdot 10^{-7}$	
Ceres	2.77	0.08	0.89	$3 \cdot 10^5$	$6 \cdot 10^5$	$2.1 \cdot 10^9$	$1 \cdot 10^{-10}$	$8 \cdot 10^{-11}$
Jupiter	5.20	0.05	1.97	$4 \cdot 10^3$		$1.0 \cdot 10^3$		$1 \cdot 10^{-4}$
Neptune	30.1	0.01			$-4 \cdot 10^3$	$1.9 \cdot 10^4$	$3 \cdot 10^{-5}$	
Pluto	39.5	0.25	-0.67	$-9 \cdot 10^4$	$-2 \cdot 10^6$	$1.5 \cdot 10^8$	$2 \cdot 10^{-9}$	$3 \cdot 10^{-9}$
Eris	67.7	0.44	-11.5	$-1 \cdot 10^6$		$1.2 \cdot 10^8$		$2 \cdot 10^{-9}$

Anyway, it is in the mutual perturbations that the difference between these bodies and the planets really stands out: the perturbations they exert on neighbouring bodies are at least three orders of magnitude smaller than the perturbations of the neighbours on themselves, and the quantitative difference with the real planets looks undisputable.

3.3. Hierarchy

In the XXth century it has become clear that the planets would have cleared the region close to their orbits, ejecting the leftovers of their accretion; conversely, the failed accretion of a planet would leave a population of smaller bodies sharing more or less the same orbital region. Soter (2006) has presented, in a paper published almost at the same time of the adoption of the IAU Resolution, interesting arguments aimed at a definition of planet based essentially on the clearing of its orbital zone.

The orbits of the eight planets of the solar system are in fact either crossed or shared (as in the case of Trojans of Jupiter) by other bodies; however, in all cases, these smaller bodies are at least a thousand times less massive than the planet in question.

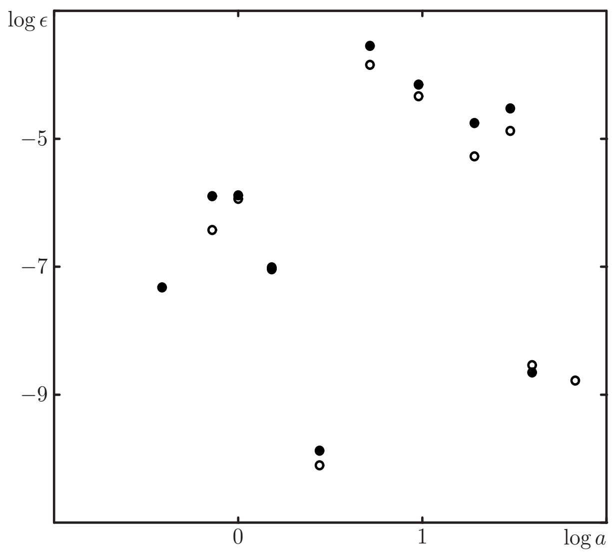

Fig. 3. *The values of* $\log \epsilon^{23}$ *(full dots) and of* $\log \epsilon_{32}$ *(empty circles) plotted against* $\log a$ *for the system formed by the eight solar system planets plus Ceres, Pluto and Eris.*

On the other hand, if we consider bodies like Ceres, Pluto or Eris, we see that this condition is not met, since their orbits are crossed by other bodies whose masses are smaller, but by less than an order of magnitude.

4. A DEFINITION BASED ON DYNAMICS

Given the previous considerations, we are now ready to give a "dynamical" definition of planet, applicable to our solar system as well as to extrasolar planetary systems.

A non deuterium burning celestial body is a planet if the following three conditions are all met for most of its existence:

1. *it moves about the Sun (alternatively, a star) along a path that does not let it approach another planet to within a distance a thousand times larger than its physical radius;*
2. *it alters, with its gravitational attraction, the motion of nearby planets and/or the star about which it orbits, by a small, yet detectable amount;*
3. *all other bodies that can come close to, or cross, its path have masses at least a thousand times smaller than that of the planet itself.*

As it is easy to see, this definition encompasses the eight classical planets, and from this point of view is equivalent to the one given in the IAU Resolution; moreover, it is applicable to extrasolar planetary systems, and the formulation of the second condition matches the way in which most extrasolar planets are nowadays discovered, i.e. by perturbations on the motion of the central star.

The third condition is formulated in such a way that no knowledge of the orbital history or the presence of resonances has to be ascertained: a difference in mass by a factor a thousand translates, for equal albedo and density, into a difference of five magnitudes, quite easy to check observationally.

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ДЕФИНИЦИЈА ПЛАНЕТЕ ИЗ УГЛА ЈЕДНОГ ДИНАМИЧАРА

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Прегледни рад по позиву

У раду су изнети аргументи да је проблему ваљане дефиниције "планете" најбоље приступити са динамичког становишта; показано је да је дефиниција планете на овај начин недвосмислена и употребљива.