SES 2013
Ninth Scientific Conference with International Participation
SPACE, ECOLOGY, SAFETY
20 – 22 November 2013, Sofia, Bulgaria

DISTRIBUTIONS OF THE SOLAR SYSTEM BODIES BY MASSES, DENSITIES AND ORBITS

Tsvetan Georgiev

New Bulgarian University 1618 Sofia,
Institute of Astronomy and NAO, 1784 Sofia

Key words: *Solar system - planets, satellites, asteroids, dwarf planets*

Abstract: *Data about heavy 72 bodies in the Solar System are used for building mass-diameter and mass-density log-log plots as well as a separate mass-density diagram using 28 massive solid bodies. The first diagram shows well-defined parabolic dependence within the dataset with a standard mean square deviation of 16%. It includes a range of 12 magnitudes by mass and 4 magnitudes by diameter, including the Sun and bodies with diameters of above 100 km. The second diagram shows a wide parabolic main sequence built on giant planet cores, planets, dwarf planets and planet satellites. On this diagram the majority of the asteroids have a high density. The third diagram presents detailed distribution of planets, dwarf planets and massive planet satellites, 28 objects in total. The mass-density diagrams reveal a few groups of bodies. For example, the satellites Jo, Europa and Moon show relatively high density and the satellites Ganymede, Calisto and Titan show relatively low density. For the purposes of completeness the rule of Titius-Bode-Dermott is shown at the end. It is presented in its contemporary notation as a linear dependence of the logarithm of the orbital period on the number of the objects with a standard mean square deviation of 23-25%. 13 objects including the Sun, the planets and the dwarf planets Ceres, Pluto, Eris and Sedna are used.*

РАЗПРЕДЕЛЕНИЯ НА ТЕЛАТА ОТ СЛЪНЧЕВАТА СИСТЕМА ПО МАСИ, ПЛЪТНОСТИ И ОРБИТИ

Цветан Георгиев

Резюме: *Данни за 72 тела от Слънчевата система са използвани за построяване на диаграми маса-диаметър и маса плътност в логаритмични координати, както и на детайлна диаграма маса-плътност за 28 масивни обекти.*

Първата диаграма показва добре очертана параболична зависимост със средно-квадратично отклонение 16%. Тя обхваща 12 порядъка по маса и 4 порядъка по диаметър – от Слънцето до планетни спътници и астероиди с диаметър около 100 км.

Втората диаграма показва широка параболична „главна последователност“ от ядра на планети-гиганти, планети, планети-джуджета и планетни спътници.

Третата диаграма представя детайлно разпределение на масивните тела, общо 28 обекта.

Диаграмите маса – плътност (втората и третата диаграми), изявяват няколко групи тела. Първите две са очевидно 4 гигантски планети и 3 големи планети (от земната група, с много висока средна плътност, без Марс). Обектите Йо, Луна и Европа, заедно с Марс, показват относително висока плътност и могат да бъдат наречени тежки малки планети. Спътниците Ганимед, Калисто, Титан и Тритон, заедно с Плутон, и показват относително ниска плътност и могат да бъдат наречени леки малки планети. Множество други обекти (Седна, Оркус, Макемаке, Япет, Тетис, Варуна и др.) следва да бъдат наречени планети -джуджета. Чак след това идват наистина малки твърди тела от Слънчевата система.

В последните две диаграми, за пълнота, е илюстрирано и правилото на Тициус-Боде-Дърмот в съвременна форма, като линейна зависимост на логаритъма на орбиталния период от номера на обекта, със средно-квадратично отклонение 23-25 %. Включени са 13 обекта, сред които Слънцето, планетите и планетите-джуджета Церера, Плутон, Ерис и Седна,

Introduction

The development of the astronomical science and the space research and technologies have lead to the specification of the primary physical parameters of a number of small bodies of the Solar system that are classified as planetary satellites, dwarf planets or asteroids. Together with these results one can see the big variety in objects with respect to their mean densities, and also the necessity to have an up-to-date comparison of the basic astronomical parameters of these bodies. The results from this comparison presented below provide a generalized picture about the bodies in the Solar system and lead to their division into groups according to their mean density. With this respect important are not only the Sun, the planets giants and the planets from the group of the Earth, but also some heavy small planets, light small planets, planets dwarfs and other small bodies. A contemporary diagram of the rule of Titius-Bode-Dermott is included in half-log coordinates, including even the dwarf Sedna.

In this paper data from 72 objects within the Solar system has been used, including the Sun, 8 planets, 33 planet satellites, 18 asteroids from the main belt, 8 dwarf planets and 4 cores from the giant planets, taken also as separate bodies. The data that has been used comes from literature that is available to the general public as well as from specialized websites that are listed in the sources section of the paper. Some data about small bodies has not high accuracy, but this is not important foe the conclusions.

Diagram mass-diameter in a log-log coordinate system

With stars and galaxies the mass-luminosity and mass-size dependencies are fundamental. Bodies from the Solar system do not illuminate and therefore, their masses and their diameters should be explored at first hand. This is illustrated by Fig. 1 in log coordinate diagram. A few facts come along as follows.

(1) The bodies from the Sun till satellites of planets with a diameter over 100 km lie within the common parabolic dependence with a standard square mean deviation of 16%. With mass and diameter there are 12 and 4 magnitudes respectively. The well-defined link within the log-log plot that could be also represented with two straight lines actually corresponds to a fractal made of two components.

(2) The Sun and the giant planets lie on a line with a slope of approx. 0.33 and standard deviation of 13%. This slope of the straight line is the same, Δ log D / Δ log M = 1/3, which corresponds to the link between the diameter and the mass of a homogeneous massive globe in log-log coordinates. he respective line is drown via the punctual representation through the point of the Earth. It is to be seen below the common parabolic dependency. The fractal size of the straight line characterizing the giant planets and the Sun is f=3 x 0.33 = 1.0. This value corresponds to the pure geometric dependency and can serve as evidence that the Sun and the giant planets are similar in the radial distribution of the density in their cores.

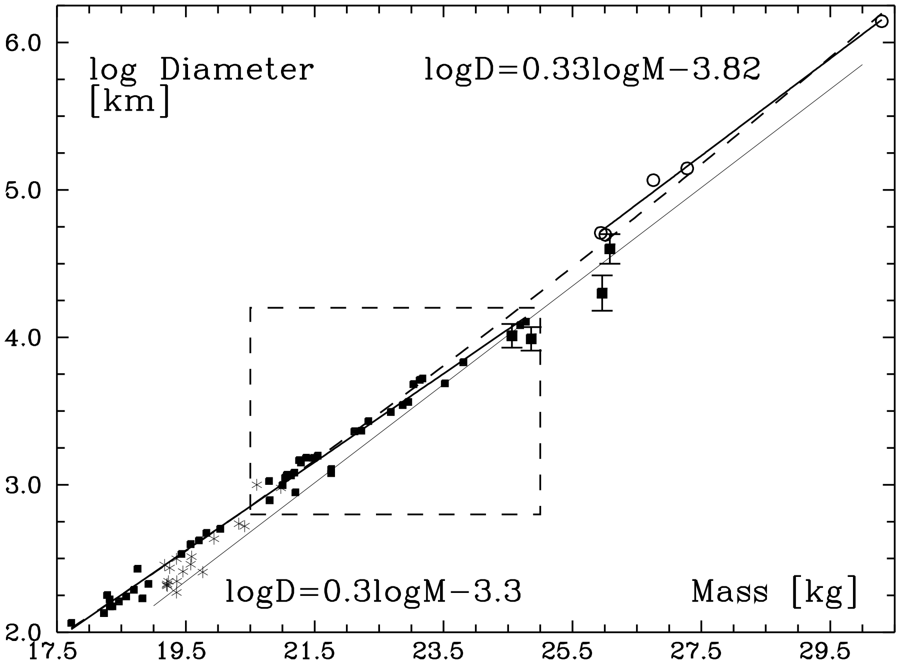

Fig. 1. Mass-diameter diagram in a log-log scale. Circles: the Sun and the four giant planets. Dots: 4 planets, 8 small planets and 33 satellites. Stars: 18 asteroids. Squares: cores of 4 giant planets. Dashed line: regression parabola without the asteroids and the cores of the giant planets. Segments: regression lines for the giant planets and the Sun (right top corner) and for the other objects, excluding the asteroids and the cores of the giant planets (left bottom corner). Straight line represents the diameter growth of a homogeneous massive globe depending on the mass, drawn via the point, representing the Earth. The rectangular includes the objects that are taken into detailed account in Fig. 3.

(3) The solid bodies - planets, dwarf planets and planet moons, excluding the asteroids, lie along a different straight line with a slope of 0.3 and standard deviation of 15%. The lower steepness of the slope (< 1/3) shows that the density increases within the group of the bodies that have higher masses, e. g. that they have heavier cores. The respective fractal value is f = 3 x 0.3 = 0.9 <> 1.0. Numerous asteroids as well as the cores of the giant planets don't follow this trend. They diverge and have lower values, which can be explained by their higher mean density. However, the data about these objects is quite inaccurate.

Mass-mean density diagram in a log-log scale

The mass-mean density diagram can be considered as analogous to the luminosity-color diagram of the stars. Fig. 2 depicts this diagram for 71 objects (excluding the Sun) and allows some conclusions to be made,.

(4) Mean densities of the solid bodies in the Solar system take over a range of one magnitude, and together with the cores of the giant planets - over a range of three magnitudes. Additionally, apart from the giant planets and the asteroids they form something like a parabolic main sequence that converges in the area of the small bodies with the density of the ice. The standard of the parabola, shown in Fig.2, accounting the planets, the dwarf planets, the satellites and the cores of Uranus and Neptune (without the cores of Jupiter and Saturn and the asteroids) is 44%.

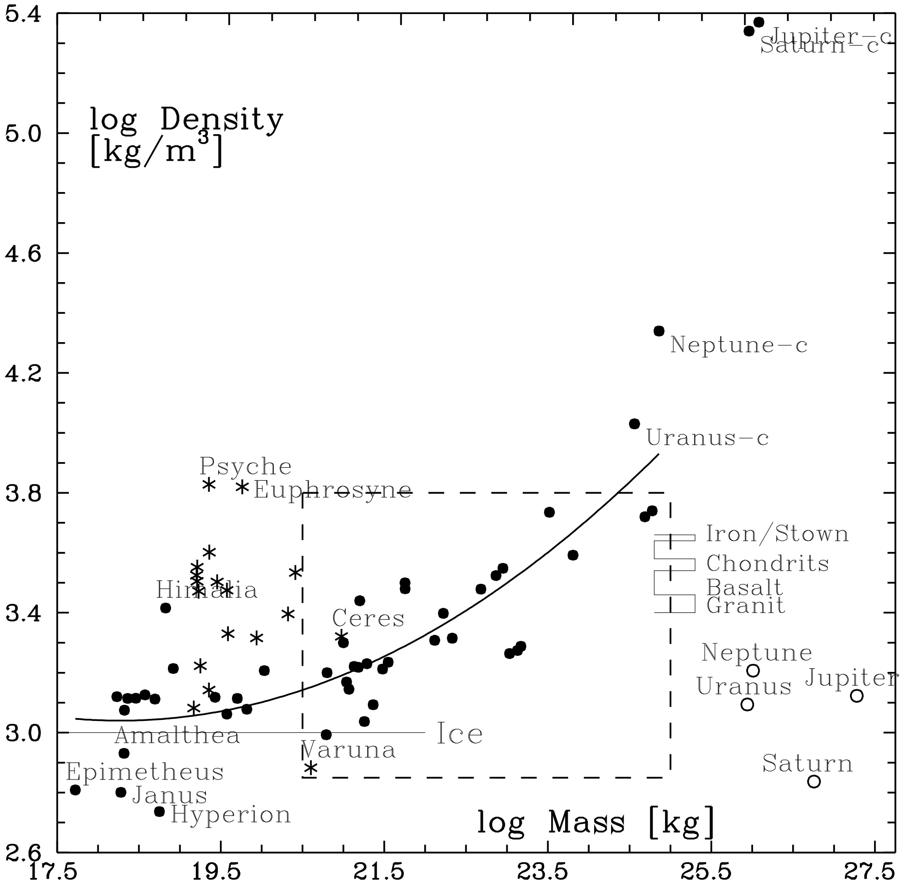

Fig. 2. Mass-mean density diagram in log-log coordinates. Circles: planets-giants. Dots: planets, dwarf planets, satellites and cores of giant planets. Curved line: regression parabola for objects represented by dots, without the cores of Jupiter and Saturn. Stars: asteroids. Horizontal segments represent the densities of ice, granite, basalt, chondrites and iron-stone meteorite. The objects in the rectangle are shown on Fig. 3.

(5) Numerous asteroids in the main sequence have considerably higher mean densities compared to the planets' satellites that are similar to them in mass. Such mean densities are characteristic for the meteorites chondrides and the satellites Jo, the Moon and Europe. However, these 3 satellites are

about 100 times more massive than the asteroids that have been considered in this paper.

(6) At least two asteroids (Psiche, Euphrosyne) have a much higher mean density, 6-7 g/cm, near to the density of iron. This is evidence that they contain more heavy metals. Among the not so big planets' satellites there is a satellite that stands out with its high density. It is the Jupiter's satellite Himalia.

The relatively high densities of some asteroids can be explained if they are to be considered as being a part of the core of a planet that broke into pieces due to a collision. It is known as Phaeton, located after the formation of the Solar system between the orbits of Mars and Jupiter.

(7) At least three not so big planets' satellites (Hyperion, Janus, Epimethius) have extremely low mean densities, lower than that of ice. It looks like these objects are kind of "dirty snow balls", similar to a comet's core.

Masses and densities of the big solid bodies

More attention needs to be paid to the more massive and the bigger bodies. These are the objects that are within the rectangles on Fig.1 and Fig.2. and they are shown in detail on Fig. 3. The objects on Fig. 3, 28 in number, are located in 4 magnitudes by mass and 1 magnitude by density. The most massive 10 of them are located in the upper half of the diagram along the diagonal, like part of the main sequence on Fig. 2.

A characteristic of the solar planetary system is the availability of two main groups of massive planets: 4 planets near to the Sun, the Earth group, with high density and 4 planets located away from the Sun, giant planets, with low mean density. It is widely considered that during the process of formation of the Solar system in the parts that are near to the Sun from the proto-planetary cloud the heavy elements have settled down. As a result, the planets within the Earth group have higher mean densities, higher than the densities of the chondrites. The two groups of planets are different also because of other astronomical parameters.

However, other groups of solid bodies may be elucidated. Figure 3 shows at least five other particularities in the density distribution of the solid bodies .

(8) Actually the mean densities of the Earth, Mercury and Venus are very high and higher than the densities of the iron-stone meteorites. However, Mars has a much lower mean density and it is much more natural that it be considered as part of the relatively smaller objects that have similar mean densities - Jo, the Moon and Europe.

(9) The massive objects that have relatively high mean density - Mars, Jo, the Moon, Europe, Eris – form approximately main sequence along the diagonal of the diagram on Fig. 3. Three trans-neptune dwarf planets can be taken into this group (Haumea, Quauar, 2007-OR10), situated to the left. This way there is a group of bodies with a mean density characteristic of granites, basalt and chondrites. These ones that are different from the others due to their relatively high mean density can be called, such as, ”heavy small planets”.

(10) The massive objects with low mean density - Ganymede, Titan and Calisto - do not follow the main sequence. They are placed in the middle bottom part of the diagram on Fig. 3. Also Triton and Pluto can be considered part of this group. This way a group of massive objects with mean density of about two times lower than the mean density of Jo, the Moon and Europe and considerably lower than the density of the rock on Earth. These objects should contain certain fractions of Hydrogen, Helium, and can be called for instance “light small planets”.

The well-expressed stratification of the big satellites of the planets according to their density can be explained with the difference in the composition of the proto-planetary medium. The objects Jo and Europe are near satellites to Jupiter that seem to have come to existence due to a much richer in heavy metals medium just like the planets that are near to the Sun. Ganymede, Calisto, Titan and Triton are far away satellites of their planets, formed like it looks from medium that is poorer on rich metals.

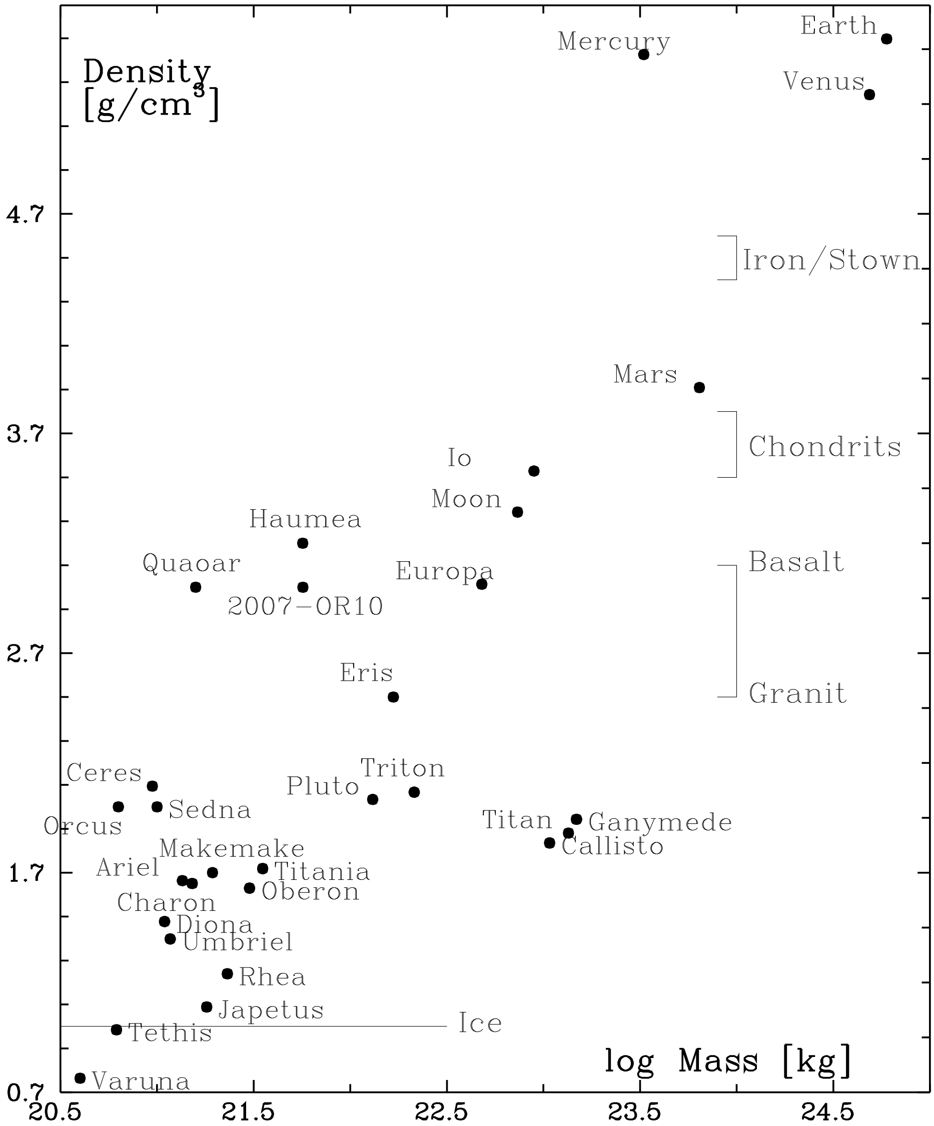

Fig. 3. Mass-mean density diagram for the massive bodies within the Solar system. The densities represented by segments correspond (top-down) to ice, granite, basalt, chondrites meteorite and iron-stone meteorite.

The Moon is a satellite with extraordinary high density and it may be considered to be part of the Earth, that came to exist after a collision of the Earth with a hypothetical planet Taya, as big and as massive as Mars (Halliday, 2000).

(11) At the left lower part of the diagram on Fig. 3 one can see a big group of lighter objects with low mean density - 10 satellites of planets, 2 asteroids (Ceres, Varuna) and 3 objects that are called today “dwarf-planets” (Sedna, Orcus, Makemake). Among these objects there are some that have density lower than the density of ice (Japetus, Thetis, Varuna). From all said above it looks like that exactly these planets should be called “dwarf-planets”.

(12) Among the objects with lower mass shown in the left bottom part of Fig. 2 there are also lighter satellites of planets and asteroids, with low densities, that indeed “small bodies in the Solar system”.

At the end, we should take into consideration that the masses and the densities of the dwarf-planets, the small satellites of the planets and the asteroids are known with an approximate exactness.

Titius-Bode-Dermott Law about the orbital periods of the planets

While considering the main characteristics of the Solar system it is necessary that an important rule be mentioned in the orbital radii and periods of the planets. It is known as the Titius-Bode law in XIX century. There is lots of information concerning this topic in the literature and on the Internet.

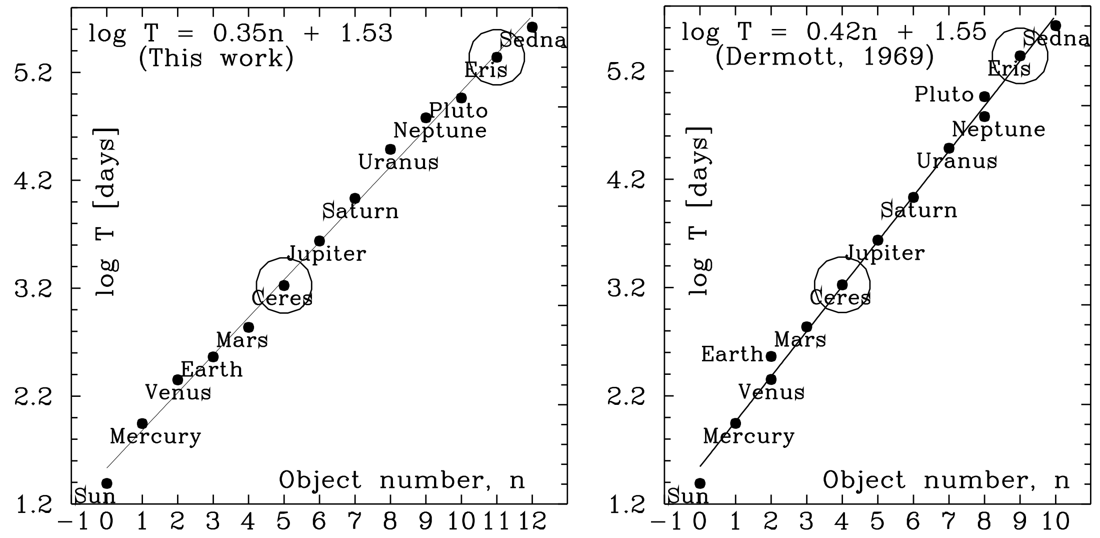

Fig. 4. Diagrams of the Titius-Bode-Dermott rule built according to the current data. To the left - taking into consideration all 13 objects. To the right - creating a group of the Earth- Venus, as well as having Neptune-Pluto as separate objects (Dermott, 1969), for a total of 11 objects. The circles correspond to the Main asteroid belt and to the Kuiper asteroid belt, containing trans-neptune dwarf planets.

In its contemporary form the rule of Titsius-Bode-Dermott (Dermott 1969, Poveda & Lara 2008) is a linear dependency of the logarithm of the orbital radius or the period on the consecutive number of the object. The radii and the periods are of equal meaning because they are directly connected with the third law of Kepler, but the usage of periods is to be preferred because it gives opportunity to have additionally the central body with its rotation period as a zero object.

Figure 4 represents two diagrams of the Titius-Bode-Dermott law built according to contemporary data together with data from the dwarf planets Eris and Sedna. On the first diagram one can see 13 objects with an angular coefficient of the straight line of 0.3 and standard deviation of 25 %. On the second diagram, following the example of Dermott (1969), the planets Venus-Earth and Neptune-Pluto are considered like objects situated along one and the same orbit, respectively number 2 and number 8. The straight line has then a higher angular coefficient of 0.42 and a lower standard deviation of 23%.

The existence of the rule of Titius-Bode-Dermott is a confirmation for the possible influence of a combination of factors that has been actively taking part in the process of forming the Solar system (Dubrule & Graner, 1994). The theoretical idea and the computer simulations show that the orbit resonance (the evenness of the orbital periods) of the big planets create in the plane of the Solar system wide rings situated in each other that do not allow for orbits to be stable over a long period of time.

Apart from that it is clear that a logarithmic law of distances can be a consequence of the process of collapse of the proto-planet disc with its axe of rotation and exponentially decreasing density towards the periphery. According to Dubrulle and Graner (1994) and Kotliarov (2008) every stable planetary or satellite system needs to satisfy this rule. There is an application of this rule in order to predict the existence of planets in other planetary systems that have not been observed ye (Poveda & Lara, 2008).

The Titius-Bode-Dermott law continues to be the subject of papers, that are not always professional. In general considering the satellites individually or grouping them in order to get right dependencies needs to be supported in a thorough way. In connection with this the astrophysicist Alan Boss, who is against such publications, says that the planetary science journal of a high authority Icarus does not accept papers that treat the topic of refining the Tutius-Bode law (Boss, 2006). However, diagrams like the ones shown in Fig.4 need certainly to be attended being another means of support to the not completely proven background to the way planetary and satellite systems came to exist.

Conclusions

(1) In this paper it has been shown that on the mass-diameter diagram in log-log coordinates the giant planets and the Sun on one side and the solid bodies on the other side lie in two well defined straight lines that correspond to fractal dimensions of 1.0 and 0.9. It is of interest whether there are

other such objects - stars from the main sequence and exoplanets follow such dependencies.

(2) On the mass-density diagrams one can see density stratification and groups of objects which allows for physical classification of the solid bodies of the Solar system in respect to their density. In this paper, as an addition to the certain kinds of massive bodies – (1), Sun, (2) giant planets, (3) planets of the Earth' group, 4 other kinds of objects are suspected – (4) – heavy small planets, (5) light small planets, (6) dwarf planets and (7) other smaller bodies.

(3) The Titius-Bode law, independently of the fact that it is not considered to be refinabled scientifically, is useful in considering of the Solar system and studying of the structure of other planetary systems.

References:

1. Boss, A., 2006, Astronomy 30 (10): 70; "Ask Astro"
2. Dermott, S. F., 1969, *Mon. Not. Roy. Astron.Soc.* 142, 143-149. "On the origin of commensurabilities in the solar system - III: the resonant structure of the solar system".
3. Dubrulle, B., Graner F., 1994, *Astron.Astrophys*. 282: 269–276. "Titius–Bode laws in the solar system. Part II: Build your own law from disk models".
4. Halliday, A. N., 2000, *Earth and Planetary Science Letters* **176** (1): 17–30, "Terrestrial accretion rates and the origin of the Moon".
5. Kotliarov, I., 2008, *Mon. Not. Roy. Astron. Soc.* 390, 1411, "A structural low in planetary systems"
6. Poveda, A., Lara P., 2008, Rev. Mex. Astron. Astrofís.,. 34, 49-52,"The exo-planetary System of 55 Cancri and the Titius-Bode Law.