

Sakholian radius-to-mass ratio postulate applied to the calculation of the mass or the radius of a sun's planet, of a planetary satellite and of a given star belonging to the Milky Way

Abstract: In this work, it is demonstrated that the ratio of the radius of a satellite to that of its center of rotation is equal to the ratio of the mass of the satellite to that of its center of rotation raised to α power. This new radius-to-mass ratio relationship postulated, is referred as Sakholian radius-to-mass ratio (SRMR) law. For a given satellite, the SRMR-law indicates clearly that the Solar system contains three categories of planets: terrestrial planets (Mercury, Venus, Earth, and Mars: $\alpha \approx 0.40$), dwarf planets (Ceres, Pluto, Haumea, Makemake, and Eris; $\alpha = 0.34$) and giant planets (Jupiter, Saturn, Uranus, and Neptune: $\alpha = 0.33$). The value of α equal to 0.34 is a theoretical argument in favor of the status of dwarf planet attributed to Pluto since the very controversial Prague 2006 IAU vote. In addition, SRMR-law is applied in the calculations of the mass and the density (volumic mass) of 64 small regular planetary moons: 24 for Jupiter ($\alpha = 0.331$), 12 for Saturn ($\alpha = 0.330$), 22 for Uranus ($\alpha = 0.334$) and 6 for Neptune ($\alpha = 0.326$). For all these 64 satellites, it is seen that $\alpha \approx 0.33$. Excellent agreements are obtained with literature masses of small regular satellites calculated assuming a constant density and using given radius. Besides, it is demonstrated that the SRMR-law can be applied to the calculation of the mass or the radius of a given star belonging to the Milky Way. For particular cases of four stars, calculations of the β -parameter give $\beta = 0.662$ for both Alpha Centauri B and Rigel and $\beta = 0.390$ for both Alpha Centauri A and Capella A. These primary results indicate the possibility to use the SRMR-law to estimate the mass or the radius of a given star of the Milky Way containing between 200 to 400 billion stars. For all the Solar system bodies (satellites and planets), the radius-to-mass ratio condition is $0.3 < \alpha < 0.4$. Out of this range, the mass or the radius determined must be revised. Then, α may be very useful parameter for modeling the size (diameter or mass) of a given celestial satellite.

Keyword. radius-to-mass ratio relationship, SRMR-law, satellite, Solar System, terrestrial planets, dwarf planets, giant planets, planetary moons, star, Milky Way.

1. Introduction

For the Solar system, six categories of astronomical bodies are currently accepted. These categories are star, planet, dwarf planet, planetary moon (or satellite), comet, and asteroid. Based on their size and composition, the planets of the Solar system were grouped into three categories before the Prague 2006 IAU General Assembly. These categories were terrestrial planets (Mercury, Venus, Earth, Mars and Pluto), gas giants (Jupiter and Saturn) and ice giants (Uranus and Neptune). But, the 2006 IAU Resolution officially stated that the Solar system consists only of eight planets which are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune. In addition, dwarf planets were also defined as a new distinct class of celestial objects [1-5]. The IAU resolves that 'planets' and other bodies in the Solar system, except satellites, be defined into three distinct categories: (1) *Planet*: 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 neighborhood around its orbit, (2) *Dwarf planet*: a 'dwarf 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, (c) has not cleared the neighborhood around its orbit, and (d) is not a satellite, (3) *Small Solar system bodies*: all other objects except satellites orbiting the Sun shall be referred to collectively as Small Solar-System Bodies. On the other hand, except Mercury and Venus, the planets of the Solar system have satellites, one moon for Earth; two for Mars; 95 for Jupiter; 83 for Saturn; 27 for Uranus, 14 for Neptune, and 5 for dwarf planet Pluto. One of the important characteristics of a Solar system body is its mass which is known to be more awkward

quantity to measure in an astronomical context [6]. Determination of physical characteristics of Solar system bodies were the subjects of many researches as well as for dwarf planets [7-10] than for planetary moons such as those of Jupiter [11, 12], Saturn [13-18], Uranus [19-22], and of Neptune [23-26], to name a few references. In general, satellites, the masses not measured are estimated by assuming a spherical volume and a constant density. In this paper, we aim to give a theoretical argument in favor of the status of dwarf planet attributed to Pluto since the very controversial Prague 2006 IAU vote and to present a simple way for the calculation of the mass and the radius of a planetary moon. In the past, many investigations [27-33] (to name a few) have been devoted to the determination of mass-radius relation which is a relationship between the radius, R , of a main-sequence star or an exoplanet (extrasolar planet) and its mass, M . For many studies, the determination of the relationship between R and M is derived from the widely used equation of state (EOS). The present study is not focused on the establishment of a relation between R and M to be compared to previous works on the matter. The goal of the present work is absolutely novel. The relationship to establish is a radius ratio and mass ratio of an orbiting body to a central body. This relationship preferred as Sakholian radius-to-mass ratio (SRMR) law is believed to be the first relation between radius ratio and mass ratio of an orbiting body to a central more massive body. Subsequently, there are any previous works in the matter for comparison. In addition, we aim to present for all the Solar system bodies (satellites and planets), a radius-to-mass ratio condition as a criteria for appreciating accuracy on the measurements of on the calculations of the mass or the radius of a given determined must be revised. This condition may be very useful for modeling the size (diameter or mass) of a given celestial satellite. The present research follows our previous works [34, 35] in the same area. The paper is organized as follows. Section 2 presents the theoretical part of the work. The results obtained are presented in section 3 along with their discussion. We conclude in section 4.

2. Theory

2.1. Hydrostatic equilibrium model

Hydrostatic equilibrium is originally the final state of an ideal liquid apart of external forces. It results in a perfectly spherical shape. The shape can be altered by rotation, inhomogeneity and/or the gravitational attraction of other bodies [4]. The equilibrium shape of a rotating and orbiting fluid body is generally that of a triaxial ellipsoid. That behavior is often expected also for solid bodies as planets, asteroids and satellites, provided they have mass enough to overcome rigid-body forces [10, 36, 37]. For most of the satellite considered in this work, the shape is not perfectly spherical. For example, Adrastea, satellite of Jupiter, has an irregular shape and measures $20 \times 16 \times 14$ km across [19].

Let us then consider in this work, Solar system bodies (Sun, planets and satellites) in hydrostatic equilibrium like fluid bodies. The shape of each of these bodies is then considered as perfectly spherical. Let us besides consider a rotating body of mass M_S and of radius R_S orbiting a more massive body of mass M_C and of radius R_C (fig.1).

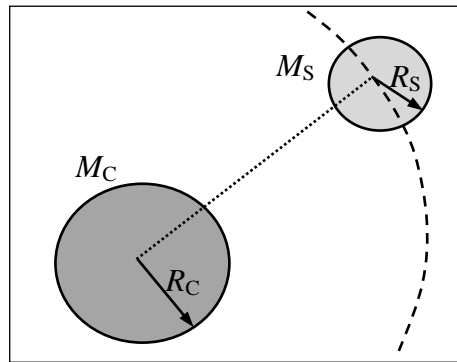


Fig.1. Satellite of mass M_S and of radius R_S orbiting a more massive body of mass M_C and of radius R_C . The two bodies are considered to be in hydrostatic equilibrium conferring them spherical shapes.

According to the Kepler's Third Law, the squares of the orbital periods T of the planets are directly proportional to the cubes of the semi-major axes r of their orbits. From this law we deduce the mass M of a planet or star:

$$M = \frac{4\pi^2 r^3}{GT^2}. \quad (1)$$

Formula (1) permits to calculate the mass, M given the orbital period, T , and orbital radius, r , of an object that is moving along a circular orbit around it. But, this formula cannot be used to calculate the mass of a planetary satellite. For some moons, the size (mass and diameter) are often measured. For example Radio Doppler data from the Galileo spacecraft's encounter with Amalthea, one of Jupiter's small inner moons, on 5 November 2002 yield a mass of $(2.08 \pm 0.15) \times 10^{18}$ kilograms. Images of Amalthea from two Voyager spacecraft in 1979 and Galileo imaging between November 1996 and June 1997 yield a volume of $(2.43 \pm 0.22) \times 10^6$ cubic kilometers [38]. But most of the planetary moons, masses are generally calculated assuming a constant density and using given radius. In addition, with an assumed constant density, the radius of a moon can be calculated using its measured mass. This is the particular case of Adrastea (moon of Jupiter). Assuming that its mean density is like that of Amalthea around 0.86 g/cm^3 [38, 39] its mass can be estimated at about 2×10^{15} kg by assuming a spherical volume with diameter of 16.4 km [40].

Let us then move on to establishing a new procedure for the calculation of the mass or the radius of a planetary satellite.

2.2. Radius-to-mass ratio relationship

As well known, the gravitational force is due to the interaction between masses. In the case of the present model described in figure 1, these masses are concentrated in a spherical shape characterized by its radius. Intuitively, there may be a relationship between the ratios M_S/R_S and M_C/R_C . As $R_S/R_C < 1$ and $M_S/M_C < 1$, we postulate that for a given system {satellite (R_S, M_S) – central body orbited (R_C, M_C)}, it is satisfied the relationship

$$\frac{R_S}{R_C} = \left(\frac{M_S}{M_C} \right)^\alpha \quad (2)$$

Equation (2) corresponds to the Sakholianradius-to-mass ratio (SRMR) Postulate. From the SRMR law(2),we pull the α -parameter

$$\alpha = \frac{\ln(R_S / R_C)}{\ln(M_S / M_C)} \quad (3)$$

If α is known,the SRMR postulate (2) permits to calculate the mass M_S of given satellite if its radius is known and vice versa. For a center of rotation (Sun of planet) in the Solar System, M_C and R_C are known. For a planet of mass M_S and of radius R_S , M_C and R_C denote the mass and the radius of the Sun. For a planetary moon of mass M_S and of radius R_S , M_C and R_C are the mass and the radius of the central body (here planet) about which the satellite orbits.

As a postulate, the law (2) is true by the consequences that one draws from it. That's what we'll check through the discussion section

3. Results and discussion

3.1. Categorization of the planets of the Solar system, radius-to-mass ratio condition

Due to its size, Pluto is not a giant planet. So, its classification must be between the category of terrestrial planets or dwarf planets. During the Prague 2006 IAU General Assembly, the vote came after eight days of contentious (antagonistic) debate that involved four separate proposals at the group's meeting in Prague. Only 424 astronomers were allowed to vote, out of some 10.000 professional astronomers around the globe[2]. The status of Pluto as a terrestrial or dwarf planet must be concluded via a scientific argument and not by vote. Using (3), we can close debate regarding this status. For this purpose, we classify Pluto into the category of dwarf planet as stated during the Prague 2006 IAU meeting. Let us then calculate α using (3) for the Solar system bodies (satellites, dwarf planets and regular planets). The results obtained are quoted in Tables 1-3.

Table 1: Values of the α -parameter for the terrestrial planets of the Solar System.

Planet	Radius R_p (km)	Mass $M_p(\times 10^{24}$ kg)	α
Mercury ^a	2 439.7	0.3301	0.3621 \approx 0.40
Venus ^a	6 051.8	4.8675	0.3672 \approx 0.40
Earth ^a	6 378.1	5.9724	0.3690 \approx 0.40
Mars ^a	3 396.2	0.6417	0.3561 \approx 0.40
Sun ^b	695 700	1 988 500	-

^a[41], ^b <https://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html>, 2022.

Table 2: Values of the α -parameter for the dwarf planets of the Solar System.

Dwarf planets	Radius R_p (km)	Mass $M_p(\times 10^{24}$ kg)	α
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Pluton ^a	1 151.253	0.013 143	0.3400 \approx 0.34
Ceres ^b	476.740	0.000 950	0.3395 \approx 0.34
Haumea ^c	780	0.004 000	0.3393 \approx 0.34
Eris ^d	1 163	0.016 608	0.3437 \approx 0.34
Makemake ^e	715	0.003 106	0.3393 \approx 0.34
Sun	695 700	1 988 500	-

^ahttps://www.princeton.edu/~willman/planetary_systems/Sol/Pluto/.2023

^b[https://fr.wikipedia.org/wiki/\(1\)_C%C3%A9r%C3%A8s#cite_note-Pitjeva2005-4.2023](https://fr.wikipedia.org/wiki/(1)_C%C3%A9r%C3%A8s#cite_note-Pitjeva2005-4.2023), ^c[8], ^d[9,42], ^e[7,43]

Table 3: Values of the α -parameter for the giant planets of the Solar System.

Planet ^a	Radius R_p (km)	Mass M_p ($\times 10^{24}$ kg)	α
Jupiter	71 492	1 898.19	0.3270 \approx 0.33
Saturn	60 268	568.34	0.2998 \approx 0.30
Uranus	25 559	86.813	0.3291 \approx 0.33
Neptune	24 764	102.413	0.3379 \approx 0.34
Sun	695 700.000	1 988 500	-

^a[41]

As stated above. Pluto is not enough massive to be classified in the category of giant planets. It is either a dwarf planet either a terrestrial planet. The results listed in the last column of each Table show clearly that Pluto is indeed a dwarf planet for which $\alpha \approx 0.34$ (Table 2) compared with the corresponding value at 0.40 for all the terrestrial planets (Table 1). For the giant planets, we find $\alpha \approx 0.33$ for Jupiter and Uranus and $\alpha \approx 0.30$ and $\alpha \approx 0.34$ respectively for Saturn and Neptune respectively. These discrepancies are not due to character gas giants (Jupiter $\alpha \approx 0.33$ and Saturn $\alpha \approx 0.30$) or ice giants (Uranus $\alpha \approx 0.33$ and Neptune $\alpha \approx 0.33$). This indicates that, the accurate value of α for all the giant planets may be $\alpha \approx 0.33$. An accurate value of Neptune may be equal to $0.334 \approx 0.33$ instead of 0.339. The anomalous value for Saturn may indicate that, the hydrostatic equilibrium model adopted is not appropriated for Saturn. Over all, we can state to the radius-to-mass ratio condition

$$0.3 < \alpha < 0.4 \quad (4)$$

Out of this range, the mass or the radius determined (measured or calculated) must be revised. The important result (4) is a tangible proof of the validity of postulate (2).

Let us give an importance consequence of condition (4) to confirm the validity of postulate (2).

For Amalthea the measured mass is $M_S = (2.08 \pm 0.15) \times 10^{18}$ kg along with a measured volume $V = (2.43 \pm 0.22) \times 10^6$ cubic km [38]. Comparison with available experimental and/or theoretical results can enlighten accuracy in the measurements for Amalthea. But without any comparison (and particularly if no literature data are available), it is possible via the present work to enlighten accuracy in the measurements as far as Amalthea is concerned. If the α -parameter for Amalthea is out of the range (3), the measurements are not precise (mass and/or volume). To verify this assertion, let us deduce the radius of Amalthea from its volume since $V = (4/3)\pi R^3$. So $R_S = 83.40$ km. Knowing that Amalthea orbits Jupiter, we get from Table 3 $M_C = M_J = 1 898.19 \times 10^{24}$ kg and $R_C = R_J = 71 492$ km. Using (3), we find

$$\alpha = \frac{\ln(83,4/71492)}{\ln(2,08/1898190000)} = 0.3273.$$

The above result is well in the range (4). So the measured mass and volume of Amalthea can be considered as accurate. This is the main important consequence of condition (4) and subsequently the validity of postulate (2).

In addition, let us demonstrate that the SRMR law (2) can lead to the mass-radius relationship between the radius, R , of a main-sequence star, and its mass, M . For this purpose, we consider the particular case of the very rough version for main-sequence stars relates the radius to an exponent of the mass (<http://astro.vaporia.com/start/massradius.html>) (in units of R_{sun} and M_{sun}):

$$R = M^{0.8}. \quad (5.a)$$

Let us then rewrite postulate (2) in solar units ($R_C = 1$ and $M_C = 1$). Let us also put $R_S = R$ and $M_S = M$. We get from postulate (2)

$$R = M^\alpha \quad (5.b)$$

Equation (5.b) is equal to equation (5.a) if $\alpha = 0.8$. Although the similitude is excellent, it should be reminded that postulate (2) is defined for the radius ratio and mass ratio of an orbiting body to a central body and not for the mass-radius relationship of a main-sequence star. Finally, the SRMR postulate (2) can be applied to an exoplanet and its central star. Comparison of equations (5.a) and (5.b) indicates clearly that postulate (2) lead to the mass-radius relationship between the radius, R , of a main-sequence star. This is a striking proof of the validity of the Sakholian radius-to-mass ratio postulate.

3.2. The α -parameter for various moons of Jupiter. Saturn. Uranus and Neptune

Let us calculate α -parameter for various moons of Jupiter, Saturn, Uranus and Neptune using (3). The results obtained are listed in Table 4.

Table 4: α -parameter for various moons of Jupiter, Saturn, Uranus and Neptune.

Satellite ^a	Radius R_S (km)	Mass M_S ($\times 10^{15}$ kg)	α
Deimos	6.200	1.4762	0.3170 \approx 0.32
Phobos	11.200	10.659	0.3190 \approx 0.32
Mars	3 396.2	641 700 000	
Satellite ^b	Radius R_S (km)	Mass M_S ($\times 10^{20}$ kg)	
Io	1 821.5	897.0	0.3685 \approx 0.37
Europa	1 561.0	478.4	0.3612 \approx 0.36
Ganymede	2 631.0	1 495	0.3495 \approx 0.35
Callisto	2 410.5	1 076.4	0.3469 \approx 0.35
Jupiter	71 492	18 981 900	
Satellite ^c	Radius R_S (km)	Mass M_S ($\times 10^{21}$ kg)	α
Miranda	236	0.0659	0.3325 \approx 0.33

Ariel	579	1.353	0.3419 \approx 0.34
Umbriel	586	1.172	0.3367 \approx 0.34
Titania	790	3.527	0.3438 \approx 0.34
Oberon	762	3.014	0.3420 \approx 0.34
Uranus	25 559	86 813	
Satellite ^d	Radius R_S (km)	Mass M_S ($\times 10^{15}$ kg)	α
Mimas	198.2	37493	0.3458 \approx 0.34
Enceladus	252.1	108022	0.3539 \approx 0.35
Tethys	531.1	617449	0.3445 \approx 0.34
Dione	561.4	1095452	0.3553 \approx 0.35
Rhea	763.8	2306518	0.3519 \approx 0.35
Lapetus	734.3	1805635	0.3482 \approx 0.35
Phoebe	106.5	8292	0.3513 \approx 0.35
Saturne	60 268	568 340 000 000	
Satellite ^e	Radius R_S (km)	Mass M_S ($\times 10^{16}$ kg)	α
Naiad	29	\approx 13	0.3295 \approx 0.33
Thalassa	40	\approx 35	0.3297 \approx 0.33
Despina	74	\approx 170	0.3245 \approx 0.32
Galatea	79	\approx 280	0.3300 = 0.33
Larissa	96	\approx 380	0.3245 \approx 0.32
Hippocamp	17.4	\approx 2.2	0.3555 \approx 0.35
Proteus	208	\approx 3900	0.3233 \approx 0.32
Triton	1353	2139000	0.3406 \approx 0.34
Neptune	24 764	10 241 300 000	

^a<https://starwalk.space/en/news/mars-moons-phobos-deimos.2023>

^b [11], ^c [13], ^d [14,43].

^e[https:// sites.google.com/carnegiescience.edu/sheppard/moons/neptunemoons](https://sites.google.com/carnegiescience.edu/sheppard/moons/neptunemoons)

The masses for Neptune moons are taken from [24].

For all the satellites considered, the data listed in table 3 indicate clearly that the radius-to-mass ratio condition (4) is rigorously satisfied. It should be underlined that, the value of α approximately equal to 0.34 for Ariel, Umbriel, Titania and Oberon doesn't mean that these moons are in the category of dwarf planets as indicated in Table 2. These moons are orbiting the Uranus planet while the dwarf planets are orbiting the Sun.

3.3. Calculation of the mass of various moons of Jupiter. Saturn. Uranus and Neptune

Using (3), we calculate the mass of various moons of Jupiter, Saturn, Uranus and Neptune. For each planet, an average value of α is used and calculated for some satellites. We obtain then $\alpha \approx 0.3310$ for the moons of Jupiter, $\alpha \approx 0.3342$ for the moons of Uranus, $\alpha \approx 0.330$ for the moons of Saturn and $\alpha \approx 0.326$ for the moons of Neptune. The masses of the moons are calculated using the following formulas

- For the moons of Jupiter

$$M_S \approx M_J \left(\frac{R_S}{R_J} \right)^\alpha = 0.0004101184 70063 \times R_S^{\frac{1}{0.3310}} \times 10^{16} \text{ kg.} \quad (6)$$

- For the moons of Uranus

$$M_S \approx M_U \left(\frac{R_S}{R_U} \right)^{\frac{1}{\alpha}} = 0.0005626559 \ 02780 \times R_S^{\frac{1}{0.3342}} \times 10^{16} \text{ kg.} \quad (7)$$

- For the moons of Saturn

$$M_S \approx M_{Sat} \left(\frac{R_S}{R_{Sat}} \right)^{\frac{1}{\alpha}} = 0.0018599307 \ 28562 \times R_S^{\frac{1}{0.330}} \times 10^{15} \text{ kg.} \quad (8)$$

- For the moons of Neptune

$$M_S \approx M_N \left(\frac{R_S}{R_N} \right)^{\frac{1}{\alpha}} = 0.0003407039 \ 65463 \times R_S^{\frac{1}{0.3260}} \times 10^{16} \text{ kg.} \quad (9)$$

The results obtained using the above equations are presented in Tables 5-8.

Table 5: Mass, radius and density of some moons of Jupiter.

Satellite	Radius R_S (km) ^a	Mass M_S ($\times 10^{16}$ kg) ^b	Mass M_S ($\times 10^{16}$ kg) ^c	density ρ (g/cm ³) ^c
Metis	21.5	≈ 3.6	4.35	1.03
Adrastea	8.2	≈ 0.2	0.24	1.04
Amalthea	83.5	208	262.18	1.08
Thebe	49.3	≈ 43	54.02	1.08
Themisto	4.5	≈ 0.07	0.038	1.00
Leda	10.75	≈ 0.52	0.53	1.02
Ersa	1.5	≈ 0.0014	0.0013	0.92
Pandia	1.5	≈ 0.0014	0.00014	0.10
Lysithea	21.1	≈ 3.6	4.11	1.04
Elara	39.95	≈ 27	28.27	1.06
Dia	2	≈ 0.0034	0.0033	0.98
Carpo	1.5	≈ 0.0014	0.0014	0.99
Valetudo	0.5	≈ 0.000052	0.000050	0.95
Euporie	1.0	≈ 0.00042	0.00041	0.98
Mneme	1.0	≈ 0.00042	0.00041	0.98
Euanthe	1.5	≈ 0.0014	0.0014	0.99
Praxidike	3.5	≈ 0.018	0.0180	1.00
Ananke	14.55	≈ 1.3	1.34	1.04
Iocaste	2.5	≈ 0.0065	0.0065	0.99
Came	23.35	≈ 5.3	5.58	1.05
Kalike	3.45	≈ 0.017	0.0173	1.01
Pasiphae	28.9	≈ 10	10.63	1.05

Sinope	17.5	≈ 2.2	2.33	1.04
Callirrhoe	4.8	≈ 0.046	0.047	1.01
Jupiter: $M_J = 189\,819\,000\,000 \cdot 10^{20}$ kg		$R_J = 71\,492$ km		

^a [40]

^{a,b} https://en.wikipedia.org/wiki/Moons_of_Jupiter.2023

^c present calculations

Note: the only satellite with measured mass is Amalthea. The masses of the inner satellites are estimated by assuming a density similar to Amalthea's (0.86 g/cm^3) [38], while the rest of the irregular satellites are estimated by assuming a spherical volume and a density of 1 g/cm^3 (https://en.wikipedia.org/wiki/Moons_of_Jupiter.2023).

Table 6: Mass, radius and density of some moons of Uranus.

Satellite	Radius R_S (km)	Mass M_S ($\times 10^{16}$ kg) ^a	Mass M_S ($\times 10^{16}$ kg) ^c	density ρ (g/cm^3) ^c
Cordelia	20.3	≈ 4.4	4.59	1.31
Ophelia	21.5	≈ 5.3	5.46	1.31
Bianca	25.5	≈ 9.2	9.10	1.31
Cressida	40	≈ 34	34.99	1.31
Desdemona	32	≈ 18	17.95	1.31
Juliet	47	≈ 56	56.69	1.30
Portia	67.5	≈ 170	167.46	1.30
Rosalind	36	≈ 25	25.53	1.31
Cupid	9	≈ 0.38	0.40	1.31
Belinda	45	≈ 49	49.77	1.30
Perdita	15	≈ 1.8	1.86	1.32
Puck	81	≈ 290	288.97	1.30
Mab	12.5	≈ 1.0	1.08	1.32
Francisco	11	≈ 0.72	0.73	1.31
Caliban	36	$\approx 25^b$	25.53	1.31
Stephano	16	≈ 2.2	2.25	1.31
Trinculo	9	≈ 0.39	0.40	1.31
Sycorax	75	$\approx 230^b$	229.53	1.30
Margaret	10	≈ 0.54	0.55	1.31
Prospero	25	≈ 8.5	8.57	1.31
Setebos	24	≈ 7.5	7.59	1.31
Ferdinand	10	≈ 0.54	0.55	1.31
Uranus: $M_U = 86813 \cdot 10^{21}$ kg		$R_U = 25\,559$ km		

^a https://en.wikipedia.org/wiki/Moons_of_Uranus.2023. Masses of all moons were calculated assuming a density of 1.3 g/cm^3 and using given radii.

^b <https://web.archive.org/web/20100105183741/http://nssdc.gsfc.nasa.gov/planetary/factsheet/uraniansatfact.html.2007>

Radii are taken from <https://nssdc.gsfc.nasa.gov/planetary/factsheet/uraniansatfact.html>

Table 7: Mass, radius and density of some moons of Saturn.

Satellite	Radius* (km) ^a	Mass ($\times 10^{15}$ kg) ^a	Mass ($\times 10^{15}$ kg) ^b	Density ρ (g/cm ³) ^b
Pan	14.1	5	5.65	0.48
Atlas	15.1	6.6	6.95	0.48
Prometheus	43.1	159.5	166.90	0.50
Pandora	40.7	137.1	140.30	0.50
Epimetheus	58.1	526.6	412.56	0.50
Janus	89.5	1897.5	1527.96	0.51
Methone	1.45	≈ 0.0063	0.0057	0.45
Aegaeon	0.33	≈ 0.000073	0.000065	0.43
Pallene	2.2	≈ 0.023	0.020	0.45
Telesto	12.4	≈ 4.0	3.83	0.48
Calypso	10.7	≈ 2.5	2.45	0.48
Polydeuces	1.3	≈ 0.0038	0.0041	0.45
Saturn : $R_S = 60\,268$ km ; $M_S = 568\,340\,000\,000.10^{15}$ kg				

^ahttps://en.wikipedia.org/wiki/Moons_of_Saturn.2023

Masses of small regular satellites were calculated assuming a density of 0.5 g/cm³.

^a[43,44], ^bPresent calculations.

Table 8: Mass, radius and density of some moons of Neptune.

Satellite	Radius (km) ^a	Mass ($\times 10^{16}$ kg) ^b	Mass ($\times 10^{16}$ kg) ^c	density ρ (g/cm ³) ^c
Nereid	172	≈ 2400	2453.73	1.15
Nereid	185	≈ 2400	3068.26	1.16
Halimede	≈ 30.5	≈ 12	12.17	1.02
Sao	≈ 20	≈ 3.4	3.34	1.00
Laomedeia	≈ 20	≈ 3.4	3.34	1.00
Psamathe	≈ 19	≈ 2.9	2.85	0.99
Neso	≈ 30	≈ 11	11.57	1.02
Neptune : $R_N = 24\,764$ km $M_N = 10\,241\,300\,000 \times 10^{16}$ kg				

^a<https://sites.google.com/carnegiescience.edu/sheppard/moons/neptunemoonsb>

^bhttps://en.wikipedia.org/wiki/Moons_of_Neptune#cite_note-Karkoschka2003-22.2023

^cPresent calculations

The masses of all irregular moons of Neptune were calculated assuming a density of 1 g/cm³.

https://en.wikipedia.org/wiki/Moons_of_Neptune.2023

The results quoted in Tables 5-8 indicate good agreement between the present calculated masses and the literature data. It should be underlined that, for Nereid, the diameter $d = (357 \pm 13)$ km gives two values, lower radius $(357 - 13)/2 = 172$ km and upper radius $(357 + 13)/2 = 185$ km, as shown in Table 7. The present mass at 2453.73×10^{16} kg is seen to agree best with the mass estimated with the lower radius at 172 km.

Besides, the masses of the irregular satellites of Jupiter are estimated assuming a density of 1.0 g/cm³ (Table 5). The masses of all moons of Uranus were calculated assuming a density of 1.3 g/cm³ (Table 6) and that of the small regular satellites of Saturn were calculated assuming a density of 0.5 g/cm³ (Table 7). Finally, the masses of all irregular moons of Neptune were

calculated assuming a density of 1 g/cm^3 (Table 8). Comparison indicate very good agreement between the present calculated density and what is assumed for all the moons considered in Table 5-8. These agreements are compatible with the spherical shape adopted for the satellites studies in this work.

3.4. Radius-to-mass ratio relationship for Alpha Centauri B, Rigel, Alpha Centauri A and Capella A stars

For the bodies of the Solar system, the above study has indicated that for all the satellites (planets or planetary moons), the radius-to-mass ratio condition $0.3 < \alpha < 0.4$ is thoroughly satisfied. In this section, we aim to establish a similar condition in the case of the Milky Way possesses between 200 to 400 billion stars.

Let us note by M_{GN} the mass of the galactic nucleus of the Galaxy (Milky Way). A star at the distance d of the center of the Milky Way orbits the galactic center with speed V given by the well-known relationship

$$V = \sqrt{\frac{GM_{GN}}{d}}. \quad (10)$$

In equation (10), $G = 6.67 \times 10^{-11} \text{ m}^3/\text{kg} \cdot \text{s}^2$ is the universal gravitational constant.

Let us estimate M_{GN} in the case of the Sun orbiting the center of the galactic nucleus at the speed $V = 250 \text{ km/s}$ and the distance $d = 28\,000 \text{ ly}$. Using (10), we obtain

$$M_{GN} = 8.3 \times 10^{32} \text{ kg} = 414 M_{\oplus}. \quad (11)$$

Let us underline that M_{GN} is not the mass of the supermassive black hole of the Milky Way. In fact, the supermassive black hole (SMBH) at our galaxy's core, Sagittarius A* is sitting at the bottom of the central gravitational potential of the Milky Way with a mass about $4 \times 10^6 M_{\oplus}$ [45].

For a given star of radius R_S and of mass M_S orbiting the galactic nucleus, we define the SRMR law as follows

$$\frac{R_S}{R_{GN}} = \left(\frac{M_S}{M_{GN}} \right)^{\beta}. \quad (12)$$

As R_{GN} is not known, the β -parameter can be evaluated considering the Sun (R_{\oplus}, M_{\oplus}) and another star (R_{OS}, M_{OS}). We obtain from (12)

$$\begin{cases} M_{\oplus} = M_{NG} \left(\frac{R_{\oplus}}{R_{NG}} \right)^{\beta} \\ M_{OS} = M_{NG} \left(\frac{R_{OS}}{R_{NG}} \right)^{\beta} \end{cases} \Rightarrow \frac{M_{OS}}{M_{\oplus}} = \left(\frac{R_{OS}}{R_{\oplus}} \right)^{\beta}. \quad (13)$$

Then

$$\beta = \frac{\ln(M_{OS} / M_{\oplus})}{\ln(R_{OS} / R_{\oplus})}. \quad (14)$$

Let us then consider particular cases of fourth stars such as Alpha Centauri B, Rigel, Alpha Centauri A and Capella A. Using (14), we obtain

- for Alpha Centauri B : $R_{ACB} = 0.863R_{\oplus}, M_{ACB} = 0.907 M_{\oplus}$
(Toliman (Alpha Centauri B) - Star Facts. <https://www.star-facts.com> › [toliman.2020](https://www.star-facts.com/alpha-centauri-b/))

$$\beta = \frac{\ln(0.907/1)}{\ln(0.863/1)} = 0.6625 \approx 0.662. \quad (15)$$

- for Rigel: $R_R = 78.9R_{\oplus}, M_R = 18 M_{\oplus}$
(<https://fr.wikipedia.org/wiki/Rigel>. 2023)

$$\beta = \frac{\ln(18/1)}{\ln(78.9/1)} = 0.661688 \approx 0.662. \quad (16)$$

- for Alpha Centauri A : $R_{ACA} = 1.217R_{\oplus}, M_{ACA} = 1.079 M_{\oplus}$ [46]

$$\beta = \frac{\ln(1.079/1)}{\ln(1.217/1)} = 0.038716 \approx 0.390. \quad (17)$$

- for Capella A (Aa): $R_{CA} = 12.2R_{\oplus}, M_{CA} = 2.69 M_{\oplus}$
(<https://theplanets.org/stars/capella-star/>).

$$\beta = \frac{\ln(2.69/1)}{\ln(12.2/1)} = 0.39558 \approx 0.390. \quad (18)$$

Let us underline that, for Capella B (Ab), we find from (<https://theplanets.org/stars/capella-star/>) the data $R_{CB} = 9.2 R_{\oplus}, M_{CB} = 2.56 M_{\oplus}$. Equation (14) gives $\beta = 0.42357$ in contrast with the assumed correct value 0.662 for both Capella B (15) and Rigel (16). In addition, from the same reference, we get for Capella H the data $R_{CH} = 0.54 R_{\oplus}, M_{CH} = 0.53 M_{\oplus}$. Equation (14) gives then $\beta = 1.030$. These results indicate that the data for Capella B and H quoted in <https://theplanets.org/stars/capella-star/> are probably inaccurate. However, this conclusion is too earlier. Systematic calculations of the β -parameter for the 100 stars closest to Earth in the Milky Way may be performed before drawing any conclusion.

4. Conclusion

We have presented in this paper a radius-to-mass ratio relationship applied to the calculations of various satellites belonging to the Solar system. Important results are obtained. Specially, it has been shown that Pluto is indeed a dwarf planet. In addition, the radius-to-mass ratio condition $0.3 < \alpha < 0.4$ is seen to be a very good criteria for appreciating accuracy of measured or calculated radius or mass of a given satellite of the Solar system. Besides, it is demonstrated that, the radius-to-mass ratio relationship can be applied to the calculation of the mass or the radius of a given star belonging to the Milky Way. Systematic calculations of the β -parameter for the 100 stars closest to Earth in the Milky Way is very challenging for the establishment of the radius-to-mass ratio condition for stars. Studies are in such direction.

Reference

- [1] Aksnes K. 2006. *Two new Pluto moons named by the IAU*. The International Astronomical Union. <https://www.iau.org/news/announcements/detail/ann06007/>
- [2] Britt R R. 2006. *Pluto Demoted: No Longer a Planet in Highly Controversial Definition* <https://www.space.com/2791-pluto-demoted-longer-planet-highly-controversial-definition.html>
- [3] Christensen. L L. 2007. *The Pluto affair: When professionals talk to professionals with the public watching*. Future Professional Communication in Astronomy (Eds. A. Heck & L. Houziaux. Mém. Acad. Roy. Belg.) <https://www.iau.org/static/publications/pluto/fp-llc2.pdf>
- [4] Probsthain K. 2018. *Size and Shape of a Celestial Body – Definition of a Planet*. <https://doi.org/10.48550/arXiv.1807.08593>.
- [4] Boyce H *et al.* 2022. *Multiwavelength Variability of Sagittarius A* in 2019 July*. The Astrophysical Journal. DOI: [10.3847/1538-4357/ac6104](https://doi.org/10.3847/1538-4357/ac6104)
- [5] Sarma. R *et al.* 2008. IAU Planet definition: Some confusion and their modifications. <https://arxiv.org/ftp/arxiv/papers/0810/0810.0993.pdf>
- [6] Hughes. D W. 2002. *Measuring the Moons' mass*. **122**. 1167. The observatory. <https://adsabs.harvard.edu/full/2002Obs...122...61H>
- [7] Brown M. E. 2013. *On the size shape and density of dwarf planet Makemake*. The Astrophysical Journal Letters. 767:L7. doi:10.1088/2041-8205/767/1/L7
- [8] Dunham E. T *et al.* 2019. *Haumea's Shape. Composition. and Internal Structure*. The Astrophysical Journal. **877**:41. <https://doi.org/10.3847/1538-4357/ab13b3>
- [9] Sicardy B *et al.* 2011. *Size, density, albedo and atmosphere limit of dwarf planet Eris from a stellar occultation*. EPSC Abstracts Vol. 6. EPSC-DPS2011-137-8. 2011 EPSC-DPS Joint Meeting 2011.
- [10] Tancredi. G and Favre. S. 2008. *Which are the dwarfs in the Solar System?* – Icarus **195**: 851-862.

- [11] Sheppard S. S. 2023.*Moons of Jupiter*. Earth & Planets Laboratory. Carnegie Institution for Science. Retrieved 7 January 2023.
- [12] Thomas. P. C. *et al.* 1998. *The Small Inner Satellites of Jupiter*. *Icarus*. **135** (1): 360–371. [doi:10.1006/icar.1998.5976](https://doi.org/10.1006/icar.1998.5976).
- [13] Jacobson R. A *et al.* 1992. *The masses of Uranus and its major satellites from voyager tracking data and Earth-based Uranian satellites data*. *The Astronomical journal*. 103. 6.
- [14] Jacobson. R. A *et al.* 2006. *The Gravity Field of the Saturnian System from Satellite Observations and Spacecraft Tracking Data*. *The Astronomical Journal*. **132** (6): 2520–2526. [doi:10.1086/508812](https://doi.org/10.1086/508812)
- [15] Jacobson. R.A *et al.* 2008. *Revised orbits of Saturn's small inner satellites*. *Astron. J.* 135. 261–263.
- [16] Porco. C.C *et al.* 2007. *Saturn's small inner satellites: Clues to their origins*. *Science* 318. 1602–1607
- [17] Thomas. P.C. *et al.* 2007a. *Hyperion's sponge-like appearance*. *Nature* 448. 50–56.
- [18] Thomas P.C. 2000. *The Shape of Triton from Limb Profiles*. *Icarus*. **148** (2): 587–588. [doi:10.1006/icar.2000.6511](https://doi.org/10.1006/icar.2000.6511)
- [19] Thomas. P. C. 1988. *Radii, shapes, and topography of the satellites of Uranus from limb coordinates*". *Icarus*. **73** (3): 427–441.
- [20] Karkoschka E. 2001. *Voyager's Eleventh Discovery of a Satellite of Uranus and Photometry and the First Size Measurements of Nine Satellites*. *Icarus*. **151** (1): 69–77
- [21] Sheppard S. S *et al.* 2005. *An Ultradeep Survey for Irregular Satellites of Uranus: Limits to Completeness*. *The Astronomical Journal*. **129** (1): 518–525.
- [22] Showalter M R. Lissauer J J. 2006. *The Second Ring-Moon System of Uranus: Discovery and Dynamics*. *Science*. **311** (5763): 973–977.
- [23] Davies M E *et al.* 1991. *A control network of Triton*. *Journal of Geophysical Research*. **96** (E1): 15. 675–681. [doi:10.1029/91JE00976](https://doi.org/10.1029/91JE00976)
- [24] Karkoschka E. 2003. *Sizes, shapes, and albedos of the inner satellites of Neptune*. *Icarus* Vol. 162. Issue 2. Pages 400–407
- [25] Kiss C *et al.* 2016. *Nereid from space: rotation, size and shape analysis from K2, Herschel and Spitzer observations*. *Monthly Notices of the Royal Astronomical Society*. **457** (3): 2908–2917.
- [26] Stooke P.J. 1994. *The surfaces of Larissa and Proteus*. *Earth Moon Planet* **65**. 31–54. <https://doi.org/10.1007/BF00572198>

- [27] Swift D. C. *et al.* 2012. *Mass-Radius Relationships for exoplanets*. The Astrophysical Journal. 744:59 (10pp). January 1 doi:10.1088/0004-637X/744/1/59.
- [28] Seager S *et al.* 2007. *Mass-Radius Relationships for solid exoplanets*. The Astrophysical Journal. 669:1279Y1297. November 10.
- [29] Bashi D *et al.* 2017. *Two empirical regimes of the planetary mass-radius relation*. A&A 604. A83. DOI: 10.1051/0004-6361/201629922.
- [30] Carvalho G. A, Marinho Jr R. M, Malheiro M. 2015. *Mass-Radius diagram for compact stars*. XXXVII Brazilian Meeting on Nuclear Physics IOP Publishing Journal of Physics: Conference Series **630**. 012058 doi:10.1088/1742-6596/630/1/012058.
- [31] Mordasini C *et al.* 2012. *Characterization of exoplanets from their formation. II. The planetary mass-radius relationship* A&A 547. A112. DOI: 10.1051/0004-6361/201118464
- [32] Alejandra D *et al.* 2019. *The white dwarf mass–radius relation and its dependence on the hydrogen envelope*. MNRAS 484. 2711–2724. doi:10.1093/mnras/stz160.
- [33] Eker Z *et al.* 2018. *Interrelated main-sequence mass–luminosity, mass–radius, and mass–effective temperature relations*. MNRAS 479. 5491–5511. doi:10.1093/mnras/sty1834.
- [34] Sakho. I. 2016. *Energy Dissipated by an Aster Accelerated in a Gravitational Field: Estimation of the Lifetime of a Planet or a Star Being Destroyed*. J.Astrophys. Aerospace Technol.**4**. 1-5.
- [35] Sakho. I. 2017. *Atomic Model of the Solar System Putting into Evidence a Tenth Celestial Object Coupled To Pluto*. J Astrophys. Aerospace Technol.**5**. 1-5.
- [36] Thomas P.C. 2007b: *Shapes of the saturnian icy satellites and their significance – Icarus* **190**: 573-584
- [37] Tricarico P. 2014. *Multilayer hydrostatic equilibrium of planets and synchronous moons: Theory and application to Ceres and to solar system moons – The Astrophysical J.***782**. 2
- [38] Anderson. J. D *et al.* 2005. *Amalthea's Density is Less Than That of Water*. Science.**308** (5726): 1291–1293. doi:10.1126/science.1110422.
- [39] Burns J A *et coll.* 2004. *"Jupiter's Ring-Moon System"(PDF)*. Jupiter: The Planet, Satellites and Magnetosphere. Cambridge University Press. pp. 241–262.
Bibcode:2004jpsm.book..241B.ISBN 978-0-521-81808-7
- [40] Grav T *et al.* 2015. *Neowise: Observations of the irregular satellites of Jupiter and Saturn*. The Astrophysical Journal. 809:3 (9pp). doi:10.1088/0004-637X/809/1/3
- [41] Williams D R. 2020. NASA. National Space Science Data Center. novembre 2020 https://fr.wikipedia.org/wiki/Syst%C3%A8me_solaire
- [42] Holler. B. J. Grundy. W.M.. Buie M.W.. Noll . K.S. 2021. *The Eris/Dysnomia system I: The orbit of Dysnomia*. Icarus 355 (2021) 114130

[43] Thomas. P. C. 2010.*Sizes, shapes, and derived properties of the saturnian satellites after the Cassini nominal mission*. *Icarus*.**208** (1): 395–401.[doi:10.1016/j.icarus.2010.01.025](https://doi.org/10.1016/j.icarus.2010.01.025).

[44] Sheppard S S. 2022.*Moons of Saturn*. Earth & Planets Laboratory, Carnegie Institution for Science. Retrieved 21 August 2022

[45] Boyce H *et al.* 2022.*Multiwavelength Variability of Sagittarius A* in 2019 July*. *The Astrophysical Journal*. 931:7 (16pp). <https://doi.org/10.3847/1538-4357/ac6104>

[46] Rachel A *et al.* 2021.*Precision Millimeter Astrometry of the α Centauri AB System*. *The Astronomical Journal*.**162** (1): 14.[doi:10.3847/1538-3881/abfaff](https://doi.org/10.3847/1538-3881/abfaff)

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