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Postprint of Statistical Study on Satellite Properties Based on Dimensionless Orbital Parameters

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Abstract

To date, 285 satellites orbiting the eight major planets of the solar system have been discovered, exhibiting rich diversity in their orbital and physical properties. Thus far, nearly all satellite research has focused on individual satellite systems or satellite groups, seemingly lacking a unified study. We propose a new orbital parameter, n , that is independent of planetary properties and depends solely on stellar radius, defined as the natural logarithm of the orbital semi-major axis in units of solar radius. The n values of satellites around different planets all exhibit a bimodal distribution, with the vast majority of satellites in the $n \gtrsim 2$ range, followed by the $n \lesssim -1$ range, while very few are in the intermediate region. From the relationship between satellite physical parameters and orbital parameters with n , we find that satellites belonging to six major planets exhibit distinct common characteristics. First, satellites with large orbital eccentricity and inclination have n values around 3.5, and they are all irregular satellites of giant planets. Second, satellites with n values between -1 and 1 are predominantly large in volume, massive, high in albedo, and slow in rotation. From the literature, we identified 11 exomoon candidates, obtained their orbital n values and satellite masses, and found that the latter are also in the -1

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Planets and Satellites: Dynamical Evolution and Stability Protoplanetary Disk
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Full Text

Preamble

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Acta Astronomica Sinica Vol. 65 No. 1 Jan., 2024 doi: 10.15940/j.cnki.0001-5245.2024.01.011 Statistical Study of the Planetary Satellites in the Framework of a Planet-irrelevant Orbit Parameter* WANG Ji-fei WANG Wei† (Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101)

Abstract

Currently, 285 natural satellites orbiting the eight solar system major planets have been discovered, exhibiting a wide range of orbital and physical properties. To date, almost all research on satellites has focused on individual satellite systems or satellite groups, seemingly lacking a unified study. This paper introduces a new orbital parameter, denoted as “ n ”, which is independent of planetary characteristics but depends only on stellar radius. It is defined as the natural logarithm of the orbital semi-major axis in units of the solar radius. The n values of satellites around different planets all exhibit a bimodal distribution, with the majority falling in the $n > 2$ range, followed by a smaller number in the $n < -1$ range, and very few located in the intermediate region. Analysis of satellite physical parameters and orbital parameters with respect to n reveals obvious common features among satellites of the six major planets. First, satellites with high orbital eccentricity and inclination tend to have n values around 3.5, and they are irregular satellites of the giant planets. Second, satellites with n values between -1 and 1 are typically characterized by large volume, high mass, high albedo, and slow rotation rates. We identified 11 exomoon candidates from the literature, obtained their orbital n values and satellite masses, and found that the massive ones also tend to fall within the $-1 < n < 1$ range, with less massive ones in other ranges. These consistent patterns suggest that the formation mechanisms of satellites in the solar system for different planets and for potential exomoons may be the same or similar.

Key words planets and satellites: fundamental parameters, planets and satellites: formation, planets and satellites: dynamical evolution and stability, pro-

toplanetary disks, exomoon

The eight major planets of the solar system show a highly uneven distribution of satellites: Mercury and Venus have none, Earth has 1, Mars has 2, Jupiter has 95, Saturn has 146, Uranus has 27, and Neptune has 14. These satellites have remarkably diverse properties: the largest are bigger than planets, while the smallest have mean diameters less than 0.3 km; some have achieved hydrostatic equilibrium and are spherical, while others have irregular shapes; some are tidally locked, while others occupy Lagrange points as Trojan satellites; some are regular satellites with small prograde circular orbits and low inclinations, likely formed in early circumplanetary gas and dust disks, while others are irregular satellites with large orbital inclinations and eccentricities, either prograde or retrograde, likely captured by giant planets.

In summary, these satellites exhibit clear differences that are obviously related to their formation locations, environments, times, and dynamical evolution. It is worth considering that the Sun's gravity dominates absolutely throughout the solar system—do these satellites orbiting different planets share some common characteristics? If so, what causes them? How do they differ from extrasolar satellites? To date, there appears to be no systematic study addressing these questions.

This paper attempts to transcend planetary systems and investigate the common features and patterns of all planetary satellites in the solar system from a holistic perspective. The data used in our calculations and discussions include physical parameters and orbital dynamical parameters of the Sun, solar system planets, and planetary natural satellites, sourced from literature [2], NASA's online database², and Johnston's compiled online databases^{3,4}. This study focuses only on planetary satellites because most physical parameters (mass, volume, etc.) and orbital parameters (semi-major axis, eccentricity, etc.) of dwarf planet and asteroid satellites lack precise measurements.

2. Stable Regions and Partitioning Phenomena of Satellite Orbits

Satellites orbiting planets have an upper limit to their semi-major axis defined by the planetary Hill sphere radius [3]. Within this radius, the planet's gravity dominates, meaning the satellite experiences stronger gravitational attraction from the planet than from the star, with the difference providing the centripetal force to balance the satellite's orbital centrifugal force. Accordingly, the Hill radius is given by:

$$R_H = a_p(1 - e_p) \sqrt[3]{\frac{m_p}{3M}}$$

where M is the solar mass, m_p is the planetary mass, and a_p and e_p are the semi-major axis and eccentricity of the planet's orbit around the Sun, respectively. Statistical analyses show that the actual stable orbital range for satellites is

typically one-half to one-third of the Hill radius, with retrograde satellites having a relatively wider stable range [4].

On the other hand, satellite orbits cannot be too short, otherwise the satellite would be torn apart by planetary tidal forces. By definition, the distance at which a satellite's self-gravity equals the tidal force exerted by the planet is the Roche radius, thus:

$$R_R = R_p$$

where R_p is the planetary radius, and ρ_p and ρ_s are the densities of the planet and satellite, respectively. Assuming the satellite is rigid and has the same density as the planet, then $R_R = 1.26R_p$.

Substituting the relevant data for the Sun and planets, we calculated the Hill radii and Roche radii for each planet, listed in . The table shows that Hill radii generally increase monotonically with planetary orbital semi-major axis, with minor adjustments due to planetary mass. From the Hill radius formula, we understand that the larger a planet's orbital semi-major axis, the smaller the solar gravitational influence on its satellites, and thus the larger the upper limit for satellite orbits. Similarly, larger planetary mass increases the gravitational influence range, also leading to larger R_H . The lower limit of satellite orbits is primarily constrained by planetary radius—larger planets have greater planet-to-satellite density ratios, resulting in larger Roche radii. For equal densities, fluid satellites have Roche radii about 80% larger than rigid satellites.

For convenience of discussion, this paper defines $n = \ln(a_s/R_\odot)$ as an orbital parameter, where a_s is the satellite orbital semi-major axis and R_\odot is the solar radius. Coincidentally, the n value corresponding to the minimum Roche radius of solar system planets is -5.1 , symmetric with the maximum Hill radius n value of 5.1 .

Actual solar system satellite distribution data fall within a slightly smaller range than the theoretical estimates, with minimum $n = -4.3069$ (Phobos) and maximum $n = 4.2524$ (Neso XIII), also roughly symmetric. [Figure 1: see original paper] shows the n values of satellites for each solar system planet. The figure reveals several features: first, most satellite orbits lie within the rigid Roche radius and Hill sphere limits, though a few satellites would be inside the Roche radius if fluid, risking disruption; second, giant planets (both gas and ice giants) show a bimodal distribution of satellite orbits, with most satellites clustering near the Hill radius, a smaller group near the Roche radius, and a gap in between—this gap is larger for Uranus and Neptune and slightly smaller for Jupiter and Saturn; third, rocky planets Earth and Mars have satellites biased toward one pole each.

[Figure 2: see original paper] presents histograms of the orbital parameter n for giant planet satellites and scatter plots of orbital eccentricity e versus n . The bimodal distribution of giant planet satellite semi-major axes is clearly visible.

For Jupiter and Saturn, satellites are more numerous at large orbital distances, with $n > 2$ satellites comprising 91.5% and 83.6% of their total satellite populations, respectively. Uranus shows a peak n distribution around -2.4 , with satellites having $n < -2$ accounting for 44.4% of its total and no satellites in the $n = [0, 1]$ range. Neptune shows no obvious peak, but has 6 satellites with positive n values and 8 with negative values, with no satellites between -0.5 and 2 . Additionally, the minimum satellite semi-major axis moves inward from Jupiter to Neptune, with amplitude consistent with Roche radius variations. In units of Roche radius, the minimum semi-major axes for Jupiter, Saturn, Uranus, and Neptune satellites are 0.37, 0.47, 0.44, and 0.44, respectively.

The widespread bimodal distribution of satellite orbital semi-major axes among solar system giant planets, with similar interval ranges, suggests a common underlying physical mechanism. It is relatively easy to understand why satellite orbits cluster near the Hill radius at the outer region—these are irregular satellites characterized by high eccentricity, large inclination, and mostly retrograde orbits, with relatively small masses and irregular shapes. These irregular satellites are generally believed to be former asteroids captured into satellite orbits by planetary gravity, with Jupiter and Neptune's irregular satellites sharing common origins that support this view [5]. Furthermore, the Hill radius equals the distance of the Sun-planet L1 or L2 Lagrange points from the star, which are potential minima and dynamically stable points in the Sun-planet plane, making satellite accumulation near the Hill radius understandable.

According to current theory, giant planet satellites in the solar system generally formed in circumplanetary disks. Taking Jupiter as an example, it captured mass from the solar nebula into a circumplanetary disk to provide material for satellite formation—a disk with about 2% of Jupiter's mass would be sufficient to form Jupiter's current regular satellites, which are relatively massive and have short orbits [6]. Early-formed satellites migrated inward due to disk viscosity and gradually fell into Jupiter, after which Jupiter would continue capturing solar nebula material to form a new generation of satellites [6]. When the current generation (possibly the fifth) formed, the circumplanetary disk had become so tenuous that it could no longer affect satellite orbits, preventing further inward migration [6]. On the other hand, because giant planets like Jupiter rotate faster than their satellites orbit, tidal dissipation transfers angular momentum from the star to the satellites, causing outward orbital migration. The rich mean-motion resonances among planetary satellites and high-precision orbital data provide evidence for tidal migration [7-8], and although tidal dissipation rates are insufficient to explain measured migration rates, considering resonance locking factors can well explain the observations [9-10]. By contrast, exoplanets form beyond the snow line and can migrate inward to near their host stars if the stellar disk has not yet dissipated [11], a mechanism that can explain hot Jupiter formation. However, after stellar disk dissipation, if a planet's orbital period is longer than the star's rotation period, the planet should also migrate outward.

Regarding the n distribution, [Figure 2: see original paper] also reveals two separate distributions at the outer region. For Jupiter's satellites, the two outer concentrations have mean n values of 3.46 ± 0.09 and 2.81 ± 0.03 . The former corresponds to the Pasiphae, Ananke, and Carme groups, while the latter corresponds to the Himalia group. In [Figure 2: see original paper], these four groups are marked with green, red, black, and blue symbols, respectively. We find that the former have higher eccentricities, orbital inclinations around 165° , and are retrograde, while the latter have eccentricities between 0.1-0.2 and inclinations around 28° . Studies show that most Himalia group satellites are gray, likely fragments from disrupted asteroids in the asteroid belt [12], while Pasiphae group satellites show distinct color differences, likely resulting from multiple collisions [13]. Saturn's satellites also show two separate distributions with means of $n = 3.36 \pm 0.14$ and $n = 2.79 \pm 0.003$, corresponding to the Norse and Inuit groups. Similar to Jupiter's system, the group farther from Saturn is mostly retrograde, while the group closer to the planet is mainly prograde. For Neptune, there appear to be two concentrations at $n = 2.5$ and 3.1 , but the small number of satellites makes this statistically insignificant. These two distributions move inward from Jupiter to Saturn and Neptune.

It should be noted that satellite group classification in the solar system is more complex than discussed above. For example, Jupiter's outer concentration actually includes two groups with slightly different semi-major axes, inclinations, and eccentricities that can be separated by different parameter fits [14].

3. Other Satellite Parameters and Semi-Major Axis

In addition to histograms of the orbital parameter n , [Figure 2: see original paper] also shows scatter distributions of satellite eccentricity, with values indicated on the right axis. Blue symbols represent prograde satellites, while red represents retrograde. Eccentricities are large and widely dispersed in the outer orbital region ($n > 2$), but approach zero in the inner orbital region ($n < 0$). This suggests that outer irregular satellites were likely captured by planets and thus have high dynamical excitation, while satellites closer to planets likely formed in circumplanetary disks.

To further investigate cross-planetary relationships between satellite parameters and semi-major axis, [Figure 3: see original paper] presents scatter plots of orbital and physical parameters for 285 solar system natural satellites versus n . The upper-left panel shows that orbital eccentricity divides into two groups: high eccentricity at large orbits and low eccentricity at small to intermediate orbits. High-eccentricity satellites all have $n > 2$, particularly Uranus XXIII with $n = 3.03$ and $e = 0.812$, the only prograde irregular satellite of Uranus. Low-eccentricity satellites all have $n < 2$, especially the 37 satellites with nearly circular orbits ($e \leq 0.0123$) that all have $n < 0$.

Orbital inclination divides into three groups: high inclination at large orbits, medium inclination at large orbits, and low inclination at small to intermediate

orbits. The sole exception is Triton, the solar system's only large retrograde satellite, with $n = -0.67$ and $i = 156.9^\circ$. A gap exists between high and medium inclinations ($55^\circ < i < 110^\circ$) with no known satellites, generally attributed to the Lidov-Kozai mechanism [15-16]. This mechanism causes oscillations of the orbital pericenter around a constant value, leading to exchange between inclination and eccentricity. Thus, nearly circular, highly inclined orbits can become high-eccentricity, lower-inclination orbits, with increasing eccentricity causing pericenter distance to shrink. Consequently, high-inclination satellites cannot remain stable for long periods.

The middle and lower four panels of [Figure 3: see original paper] show that satellite rotation period, albedo, equivalent spherical diameter, and mass all exhibit a “high in the middle, low on both sides” pattern, with the “middle” primarily in the $-1 < n < 1$ range.

Except for Mercury and Venus, which are relatively close to the Sun, other solar system planets rotate relatively quickly, with periods around 1 day. The fastest is Jupiter (9h50min) and the slowest is Mars (24h37min). Solar system satellite rotation rates span a wide range, from Deimos' s 0.3 days to Iapetus' s 79.5 days. The top 12 satellites by rotation period are: Iapetus (79.5 d), Moon (27.3 d), Callisto (16.7 d), Titan (15.9 d), Oberon (13.5 d), Titania (8.7 d), Ganymede (7.2 d), Triton (5.9 d), Hyperion (4.9 d), Rhea (4.5 d), Umbriel (4.1 d), and Europa (3.6 d). Except for Iapetus, all these satellites have $-1 < n < 1$. Because rotation periods cover such a wide range, subtle trends are not visible on a linear scale, so [Figure 4: see original paper] plots the logarithm of the ratio of satellite rotation period (P_{rot}) to orbital period (P_{orb}) versus n . The period ratio mainly falls in two ranges: for $n < 2$, the ratio is near 1 (log value 0), while for $n > 2$, it falls in $[10^{-3}, 10^{-5}]$. This shows that rotation periods are longest in the middle region, likely because these satellites are tidally locked to their parent planets, making rotation periods similar to orbital periods and causing rotation period to increase with orbital semi-major axis. Satellites with $n > 2$ rotate rapidly, further supporting their captured origin.

To date, 73 satellites have albedo data. The top 9 by albedo are: Telesto (1.0), Enceladus (0.96), Calypso (0.95), Tethys (0.78), Triton (0.72), Europa (0.67), Rhea (0.65), Dione (0.65), and Io (0.63), all with orbital parameters in $-1.1 < n < 0$. The 28 satellites with moderate albedo (0.1-0.6) still occupy the middle n range ($-2.01 < n < 2.34$), while the 36 satellites with albedo < 0.1 are distributed at both ends ($-4.31 < n < -1.14$ and $2.77 < n < 3.56$). Albedo is a static physical property that should be independent of semi-major axis. We propose that, on one hand, high-albedo satellites are nearly spherical regular satellites with surfaces dominated by water ice, giving high reflectivity. On the other hand, satellites close to planets have lower surface smoothness due to tidal effects, as do distant irregular satellites, resulting in lower albedos at both ends. However, we cannot exclude observational selection effects—some middle-orbit satellites may be too dark to measure accurate albedos.

For satellite mass and radius, since densities of satellites, especially regular ones,

do not differ greatly, diameter and mass trends are very similar. Satellite mass is extremely difficult to measure and can only be obtained through dynamical methods, so only 41 of the 285 satellites have mass measurements. We therefore focus on diameter. Satellites in the middle region have large masses and diameters, while those at both ends are small. The top 10 satellites by equivalent spherical diameter are (M represents Earth mass): Ganymede (5266 km, 0.023 M), Callisto (4821 km, 0.018 M), Io (3643 km, 0.015 M), Moon (3474 km, 0.012 M), Europa (3122 km, 0.008 M), Triton (2707 km, 0.004 M), Titania (1578 km, 0.0006 M), Rhea (1528 km, 0.0003 M), and Oberon (1523 km, 0.0005 M), all with orbital parameters in $-1 < n < 1$. These are also the 10 most massive satellites. These 10 satellites belong to 5 different planetary systems, and except for Earth, all are multi-satellite systems, showing this pattern holds for all satellite systems. This phenomenon is understandable: irregular satellites in distant orbits were generally captured from small solar system bodies or their fragments and are thus small, while satellites very close to planets are also small, either forming small or being remnants of larger satellites disrupted by giant planet tidal forces. The formation of innermost satellites remains undetermined. Notably, the mass and diameter distributions of solar system planets also show high middle and low ends.

In summary, the six satellite systems of the solar system share common features: satellites near $n = 0$ have relatively large diameters and masses, slow rotation, and high albedo, while irregular satellites near $n = 3.5$ have large eccentricities and inclinations. This suggests that despite different planetary properties and diverse satellites, their formation and evolution mechanisms should be the same or similar. Other common features may await discovery—for example, Europa at $n = 0.07$ is the smoothest known body in the solar system, lacking large-scale features like mountains and craters, and other satellites with small $|n|$ are also relatively smooth. Satellites in this region experience weak planetary tidal effects and remain regular, thus maintaining good sphericity. However, due to lack of systematic data, we do not expand on this here.

We also attempted to normalize satellite orbits using planet-related parameters such as planetary radius or planetary Hill radius as denominators, yielding orbital parameters n_r and n_H , respectively. [Figure 5: see original paper] shows satellite eccentricity distributions versus n_r and n_H . The partitioning phenomenon persists, but orbital parameter distributions among different satellite systems show some offset. For eccentricity, satellites mainly concentrate near $n = 3.2$, with Jovian and Saturnian outer satellites having very similar n values. For the 201 satellites with $n > 3$, the n dispersion (standard deviation) is only 0.15. However, using n_r and n_H , the distributions are more dispersed, especially for n_H , where Saturnian and Jovian satellites show clear separation. Similarly, for the same 201 satellites with $n_r > 5.55$, the n_r standard deviation is 0.25, while the n_H standard deviation is 0.20. This trend also appears at the inner orbital end: n_r and n_H are more dispersed than n . Therefore, the orbital parameter n normalized by solar radius is more suitable for this work than n_r and n_H normalized by planetary radius and Hill radius, as it better unifies

different solar system satellite systems and facilitates commonality studies.

4. Exoplanet Satellite Candidates

As of September 20, 2023, humans have discovered over 5,523 exoplanets⁵. The solar system has 285 known satellites, and exoplanets should also host numerous satellites [1], but no exomoons have been confirmed, mainly because satellite signals are too weak and drowned out by planetary signals. Currently, several exomoon candidates have been found primarily through transit transmission spectroscopy, direct imaging, microlensing, and transit methods. We compile data for less controversial candidates [17-27] in for discussion (M_J represents Jupiter mass). Candidates with significant controversy are excluded. For example, Fox et al. [28] used Transit Time Variation (TTV) to identify possible satellites in 8 Kepler systems, but Kipping [29] conducted independent analyses of 6 of them, concluding they are unlikely to be satellites. Therefore, these candidate satellites are not included in this work.

The table shows that exomoon candidate n values span the same range as solar system satellites, with maximum 4.53 and minimum -2.10 . Satellite masses are also largest in the $-1 < n < 1$ range and smaller in other ranges. Candidate Kepler-1625b-i has $n = 1$ and mass 19 Earth masses; Kepler-1708b-i has $n = -0.04$, mass about 37 Earth masses, and radius 2.6 Earth radii; WASP-12b-i has $n = -0.35$, mass 0.57-6.4 Earth masses, and radius 6.4 Earth radii. These satellites are generally larger than solar system satellites, likely due to observational selection effects—only the largest satellites can be detected.

Notably, among these 11 exomoon candidates, most orbits lie within the planetary Hill sphere, but HD 189733b-ii and WASP-12b-i have semi-major axes significantly larger than their planet's Hill radius, meaning these satellites (if real) may be in the process of escaping planetary gravity and should show clear temporal variation in their dynamical parameters. These two exomoon candidates merit follow-up observations.

All solar system planets except Mercury and Venus have satellites. These planets have different properties, and their satellites are diverse. Previous studies generally focused on individual satellite systems or even specific groups within a system. Considering that solar gravity dominates the solar system, this paper proposes an orbital parameter n independent of planetary properties but dependent on stellar properties—the logarithm of satellite semi-major axis normalized by stellar radius. We find that satellites of major planets show a bimodal n distribution, with many satellites at both ends and very few in the middle, showing an obvious gap. For gas giants Jupiter and Saturn, over 80% of satellites are in outer orbits, with at least two concentrations at $n \approx 3$ and $n \approx 3.5$ —the former mostly prograde with relatively high eccentricity, the latter retrograde with even higher eccentricity. Ice giant satellites mainly cluster near the Roche radius.

The bimodal orbital distribution can be explained by formation and evolution theory. First, inner satellites mainly formed in circumplanetary disks and

may have experienced multiple cycles of satellite formation, inward migration, and fall into the planet [6]. Before disk dissipation, disk viscosity caused inward migration; after dissipation, because giant planets rotate faster than their satellites orbit, tidal effects cause outward migration. Therefore, some middle-region satellites should have migrated outward from inner orbits, but migration timescale is inversely proportional to orbital length to the $11/2$ power, so farther orbits migrate slower, resulting in fewer satellites in this region. For example, Titan likely formed in an inner orbit and migrated to its current position [10], with a migration timescale of about 10 billion years—longer without tidal resonance. Outer satellites are mainly captured asteroids or fragments from the asteroid belt with originally similar dynamical properties, thus concentrated orbits [6].

Notably, although Jupiter's radius and mass are 1.2 and 3.34 times Saturn's, respectively, outer Jovian and Saturnian satellites have very similar n distributions, suggesting similar external origins. Following this pattern, Neptune should have many undiscovered distant satellites.

Using orbital parameter n as the horizontal axis, we analyzed distributions of orbital eccentricity, inclination, rotation period, albedo, diameter, and mass. We find that eccentricity is near zero for $n < 1$ and large for $n > 2$, mostly concentrated in $3 < n < 4$ with a most probable value of 0.25. Inclination shows three ranges: near zero for $n \leq 1$, and for $n > 2$, two parts—one at 20° – 60° (prograde) and more at 140° – 180° (retrograde).

Physical parameters including rotation period, albedo, diameter, and mass all show high middle and low ends. The rotation period trend mainly arises because short-period satellites are mostly tidally locked to their parent planets, making rotation period increase linearly with orbital period, while outer irregular satellites are not tidally locked and thus have short periods. The other three parameters reflect that planetary mass is largest in the $-1 < n < 1$ range, giving largest diameters, with satellites neither overly affected by planetary tides nor too small to achieve hydrostatic equilibrium.

In summary, the 285 satellites of six solar system planets show consistent overall trends, and extrasolar satellites follow similar mass distribution patterns. Satellite formation and evolution should be the same or similar across the six solar system planets and currently known exomoon systems. More data on solar system and extrasolar satellites will help better understand satellite formation and evolution.

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