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An Integrated Review of Pluto-Charon Binary Syatem

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Abstract:

The Pluto-Charon binary system is a significant celestial configuration in the Kuiper belt, it is the first Kuiper-belt binary to be discovered. The study of the Pluto-Charon binary system is helpful for the understanding of planetary formation and evolution and Kuipe-belt objects. The surface feature of the binary and the evolution of the system related to the Sun or its satellites and rings have been hot in research on the Pluto-Charon system. For example, most study hold a view that the Pluto-Charon binary was formed by a giant impact. However, the internal structure and formation remain partly unexplored. This review paper compiles literature on the physical properties, formation, and basic dynamics of the Pluto-Charon system. Observational data from the New Horizons mission has advanced the understanding of the system, the review overviewed the characteristics of the Pluto-Charon binary system from the observation and analysis in the current research, such as the surface material of the two bodies. The paper also added a basic introduction to the binary system.

Keywords: Kuiper belt - planets and satellites: formation - planets and satellites: individual -planets and satellites: general - binary systems

1. Introduction

A binary system is a ubiquitous celestial system which consist of two celestial body that orbits around their centre of mass. In this system, the motion of the binary celestial bodies is governed by the mutual influence of their gravitational forces. Binary stars perform isochronous circular motion around the barycentre in their respective orbits. To date, potential explanations about the formation and evaluation of binary systems are more refined with extensive observatory and detection data. The researches on binary systems likely contribute to the study of stellar evolution, gravitational wave astronomy, astrometry, and celestial mechanics.

Pluto and Charon, Kuiper Belt Objects (KBOs), form a binary system, making them the first KBO binary (KBB) to be discovered [1]. Pluto was the initial KBO to be found which is recognized as the largest dwarf planet in the kuiper belt. Pluto was discovered in 1930, following the detection of one of its most massive satellites Charon in 1978 [1]. The Pluto-Charon binary system exhibits some distinctive features as a generalized planet and a moon. It is already known that Charon has a relatively large mass compared to Pluto, with a ratio close to $1:10$, which is unusual among planetary satellites. Moreover, the centre of gravity is located outside either body, so of course, they both orbit around their common centre of mass. Pluto and Charon mutually are in tidal locking, presenting a fixed face towards each other. Besides, the interaction in the system and its long evolution may be some of the factors of the interesting terrain and surface material of Pluto and Charon

The latest research about the Pluto-Charon binary system is promising and substantial, such as innovative formation channels for the origin of the system and the analyses of a wide range of geologic features and dynamic atmosphere phenomena [1]. There are also some uncertainties and research gaps like how Pluto has sustained geological activity for billions of years after its formation, the internal structure and formation of Pluto and Charon, and also their roles in the early stages of the Solar system history [2]. These point toward a wide field for future research.

The research on the Pluto-Charon system is meaningful. Firstly, their unique properties, like the trajectory and dynamic process, which provide valuable information for the study of gravitational interaction and the evolution of binary systems. In the second place, it plays a role for understanding the Solar system's origin and subsequent evolution. Moreover, this series of research is significant in the understanding of the moons of Pluto and other KBOs and rings.

The purpose of this paper is to synthesize the researches on the Pluto-Charon binary system that are scattered across various literature, providing a comprehensive and systematic perspective for readers.

2. Theoretical Foundation

2.1 The Definition of Binary Star System

In a binary star system, two celestial bodies are bound together by their mutual gravitational attraction, causing them to revolve around their barycentre. The main bodies in the system can be a pair of main sequence stars (Sirius AB), giant stars (γ Leonis), white dwarfs (ZTF J1539+5027), neutron stars (PSRJ1846-0513), black holes, and dwarf planets (Pluto-Charon binary system), etc [3]. The number of known binaries has now surpassed 70 and is rapidly increasing [4]. In addition, stars in a binary system may undergo stellar mass transfer, tidal locking, and stellar mergers, which significantly influence the evolution of stars. A binary system obeys Newton's law of gravitation and Kepler's law. Observations and research of binary systems are helpful for the understanding of the features and evolution of celestial bodies, such as stellar mass transfer.

2.2 Classification of Binary System

The classification of binary systems can be based on various criteria. In physical interaction, binary systems can be observed as physical binaries and optical binaries. In a physical binary system, two celestial bodies are capable influenced by others gravitational attraction, which are physically associated. Oppositely, optical binaries are pairs of stars that appear extremely close together in the line of sight observing from the Earth, the stars do not orbit their barycentre. Therefore, the Pluto-Charon binary which will be discussed in the following text is physical.

As a characteristic of observation, binary systems can be classified as visual binaries and spectroscopy binaries. A visual binary system means the pair of celestial bodies in the system can be distinguished by a telescope. A visual binary can be either a physical binary or an optical binary since visually discerning them does not infer the physical connection in terms of their intrinsic properties. In a spectroscopy binary system, stars are detected by spectral analysis. Due to the considerable distance, they cannot be distinguished through visual observation. The Pluto-Charon binary is not likely a visual binary or a spectroscopy binary. The former is because the angular distance between Pluto and Charon is relatively much small for which they are hard to be distinguished as two independent celestial bodies using telescopes. The latter is because the relative speed of Pluto and Charon is insufficient to produce the Doppler effect, which is difficult to resolve using spectral analysis since the low variation of the spectral line will be highly affected by the resolution of the spectrograph and background noise. In properties of orbit, binary systems can be classified as close binaries and wide binaries. In a close binary system, the distance between the two stars is relatively close and are affected by others gravitational attraction. Besides, it is possible to occur mass transfer in this system. In wide binaries, the distance between the two stars is relatively large and lack of significant mutual interaction. A wide binary system is likely to experience perturbations by external gravitational attraction [1]. The proto-Pluto-Charon system is considered to be a highly inclined wide binary [1]. Binary systems can be categorized as eclipsing binaries if the stars in the system eclipsed mutually, causing periodic variations in luminosity [5]. The Pluto-Charon binary is not considered as eclipsing binary since the orbital plane of them is not coplanar with the line of sight of the observation on the Earth. A given binary can fall into more than one of these classifications.

2.3 The Evolution of Binary System

The formation and evolution of a binary star system are influenced by various factors, including the star's initial mass and orbital parameters. In common envelop (CE), one of the stars in the system undergoes a violent expansion with substantial mass loss, enveloping the other star within the outer layer, thereby forming a CE [6]. The process of CE highly determines the outcome of a binary star system. The two stars may coalesce into a single star. Or the CE may be ejected, leading to the formation of a short-period binary. Besides, the orbital period and inclination angle influence the dynamic characteristics and evolution of a binary system, especially during the period of mass transfer and CE. It is because these determine the interaction and the exchange of energy and angular momentum. For instance, if a star starts to fill with its Roche lobe (RLOF) and transfer the substance to its companion, the orbital period and inclination angle may influence the effectiveness and stability of the process of transfer [7]. In a binary system, the more massive star exhausts its core fuel first and expands to become a supergiant, this might transfer matter to its companion through the process of RLOF and CE [8]. The process may lead to variations in the parameters of the system's orbit, including a shrinking orbital period.

3. Physical Properties of Pluto-Charon Binary System

3.1 Introduction to the Pluto-Charon Binary System

The Pluto-Charon binary system is a complex celestial system composed of the dwarf planet Pluto and its largest moon Charon, the binary is located in the Kuiper belt at the edge of the Solar System. Pluto was first discovered in 1930 and its biggest companion Charon was discovered in 1978. Pluto is considered to be the largest planet in the Kuiper belt (which was discovered in 1992), was originated around 4.5 billion years ago during the early period of planetary [9]. The NEW Horizons spacecraft from NASA has conducted the initial exploration mission to Pluto, reaching its zenith on 14 July 2015 [9]. It collected several data on Pluto and its system including Charon. The system is renowned for its unique dynamical properties and rich group of satellites, providing valuable information for the study of planetary formation and evaluation. Pluto and Charon have masses $M_P = 1.3\times10^{25} g$ and $M_C = 1.5\times10^{24} g$, and have radii $R_P = 1188.3km$, $R_C = 606km$ [4]. It follows from these that Pluto and Charon have densities $\rho_P = 1854kg/m^3$, and $\rho_C = 1701kg/m^3$ [1]. The mass ratio of Charon to Pluto is 0.1217, this suggests that the system's centre of mass is located outside the major body [10].

3.2 Observational Data and Orbital Parameters

The orbital separation between Pluto and Charon is 16.97 times of the Pluto radii (RP), approximately $20400km$, indicating an eccentricity that is effectively zero [2]. Besides, the system is tidally locked, and the orientation of their binary orbit is inclined relative to the orbital of the major planets, with an inclination exploration mission to Pluto, and its orbital inclination (iPC) is $96°$ [2]. The orbital period of Pluto and Charon is 6.38 days, the relatively distance between them is $2\times10^7 m$. Moreover, Charon's considerable inclination to the orbital plane of Pluto is about 119 degrees, which is rare among the Solar System's satellites [1]. Pluto's orbit itself is a flat ellipse with an eccentricity of 0.251, a semi-major axis of $39.5AU$, an orbital inclination of $17°$, and an orbital period of 248 years [6]. Numerical simulations indicate that about 0.02% of the binary system total mass may ultimately become the debris around the binary, initially located on markedly eccentric orbits spanning from distances of 5-10 RP to 30 RP [2]. Additionally, the possible dust rings in the Pluto-Charon binary system, with optical depths ranging from 4×10^{-11} to 5×10^{-6}, likely to be composed of the material resulting from collisions between Pluto's satellites and debris in Kuiper Belt.

On July 14, 2015, the New Horizons spacecraft made its closest pass to Pluto, which $13691km$ from the center of Pluto [10]. This historic flyby has collected over 50 gigabits of data on the Pluto system, providing much valuable first-hand information for the study of geology, atmosphere, and surface features of Pluto's system. According to the detection, the surface features of Pluto are rich, which have considerable geological diversity and complexity. There is a heart-shaped region Tombaugh Reggio with $2000km$ in width, and in this region there are vast frozen plains with no crater [6]. One of frozen plain named Sputnik is divided by narrow and shallow troughs and there is dark matter in some of the troughs [6]. Moreover, young frozen mountains up to $3500m$ that formed within the last 100 million years provides evidence of Pluto's geological activity. Spectral data reveal the distribution of a large amount of frozen methane and differences in methane ice in different regions. New Horizons detected that Pluto's atmosphere extends $1600km$ above its surface, indicating that the nitrogen-rich atmosphere of Pluto extends widely [6]. Charon's surface is likely composed more of water ice, has significantly higher amount of muted colors, a low albedo, and thin atmosphere, about $0.1mb$ [2].

3.3 Formation and Evolution of Pluto-Charon Binary

Pluto is believed to have formed in the initial era of the Solar System, in the residual planetesimal disk that featured an outer boundary of approximately $30AU$ [7]. The Pluto-Charon binary system's formation involves three possible mechanisms: a giant impact, gravitational collapse, and dissipative gravitational interactions. In giant impact mechanism, it suggests that the Pluto-Charon system is formed through a giant collision between precursors with faily large masses [2]. In this scenario, the precursor of Charon collided with proto-Pluto with approximately escape velocity and then combined with Pluto and ejected a large debris disk [1]. Charon is thought to be formed from the residual mantle matter after the collision. The gravitational collapse model involves the gravitational collision and fission of a massive rotating pebble cloud. The mass of the pebble cloud needs to be greater than or equal to the mass of the system [1, 2]. However, during the formative period of the binary and because of the mass loss, forming a pebble cloud like this has a low possibility from simulations. Besides, this model posits an initial composition among all the celestial bodies in the system; however, this prediction is not consistent with the rock-to-ice ratio between Charon and Pluto [2]. In the mechanism of dissipative gravitational interactions, there is required for a large midplane reservoir which supplying necessary dynamical drag to slow down the encounter velocities between larger Kuiper belt objects (KBOs) [2]. However, as those larger KBOs grow to the size of Charon or larger, the ratio of the pebbles' surface densities of pebbles of celestials in the 100-km class will decrease to 10 or lower, which makes it difficult to form a binary [2]. The Pluto-Charon binary system is suggested to have formed by a large impact, which would lead to a complete ice-rock differentiation and the formation of the early subsurface ocean of Pluto. Furthermore, there is rich volatile matter in the land and atmosphere of Pluto, which may originate from the organic material during the accretion

4. Basic Principles and Dynamics

The motion of the Pluto-Charon binary system obeys Kepler's laws, which means the orbital period squared is proportional to the semi-major axis cubed of the orbit. The binary performs uniform circular motion around their common centre of mass. The gravitational attraction supplies the centripetal force needed for each celestial body, and the magnitude of the forces on both bodies is equal. They follow the Newton's law of gravitation, which is:

$$F = G\frac{m_1 m_2}{r^2} \quad (1)$$

Here, F is the gravitational force. G is the gravitational constant. The masses of the two stars are m_1 and m_2. r is the distance between a binary. The motion of the stars in a binary system can be described by Kepler's third law, with the formula:

$$T^2 = \frac{4\pi^2 a^3}{G(m_1 + m_2)} \quad (2)$$

Where T is the total period of the system, a is the average value of the semi-major axes of the orbits of the binary stars. This indicates that the time period and angular velocities of the two stars are the same. The relative motion of the two stars in a binary system obeys the conservation of angular momentum, which is expressed as:

$$L = I\omega = mr^2\omega \quad (3)$$

Where L is a system's total angular momentum, I is the momentum of inertia, ω is the angular velocity. Since the angular momenta of the two stars are equal, it can be described as:

$$m_1 r_1 \omega^2 = m_2 r_2 \omega^2 \quad (4)$$

Hence, the mass of the two stars is inversely proportional to the distances from their barycentre, which is:

$$\frac{m_1}{m_2} = \frac{r_2}{r_1} \quad (5)$$

This implies that the celestial body with a more substantial body is closer to the barycentre. The total energy conserved in a binary system is:

$$EE_1 = \frac{M_1\vec{V}_1^2}{2} + \frac{M_1\vec{V}_2^2}{2} - \frac{GM_1M_2}{r} = \frac{\mu\vec{V}^2}{2} - \frac{GM_1M_2}{r} = -\frac{GM_1M_2}{r} \quad (6)$$

Where r is the two bodies. The angular momentum of the orbit is perpendicular to orbital plane which is expressed as [5]:

$$\vec{J}_{orb} = M_1\vec{V}_1 \times \vec{r}_1 + M_2\vec{V}_2 \times \vec{r}_2 = \mu\vec{V} \times \vec{r} \quad (7)$$

Suggests that a binary's eccentricity is zero, r and V are not depend on time, where V is the velocities of the bodies. Therefore, the orbital angular momentum can be described as:

$$\left|\vec{J}_{orb}\right| = \mu Va \quad (8)$$

5 Conclusion

The Pluto-Charon binary system has complex dynamical evolution and rich geological features. It is significant for the understanding of KBO and evolution of the Solar system. The review introduced the theoretical foundation of a binary system such as the definition, principles, dynamics, and classifications. Moreover, the paper gave a review of the features, observational data, and formation of the Pluto-Charon binary system. Future research directions could be aimed toward the problems of the geologically active Pluto, the evolution of the Pluto-Charon binary system with the Solar system, the potential debris disks and rings, and other KBO objects. Continued investigation of the Pluto-Charon system is essential for deepening the understanding of planetary formation and celestial mechanics.

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