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## THE DWARF PLANET 136199 HAUMEA AND ITS SATELLITES AND RINGS

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**Summary.** *Haumea is the first of the dwarf planets discovered since the discovery of Pluto in 1930. However, its formal recognition as a dwarf planet was delayed for several years due to a dispute over who should be considered the discoverer of this celestial object. The first announcement of its discovery was made by a Spanish team led by José Luis Ortiz Moreno. When registering its discovery, the object was assigned the temporary designation "2003 EL61", according to the date of the image in which the object was found by the Spanish group. And only in September 2008 was the name of this object Haumea, proposed by the Americans, officially approved and included in the newly created in 2006 class of dwarf planets. It became the fifth dwarf planet and the fourth plutoid, along with Pluto, Eris and Makemake. In September 2006, Brown's team submitted proposals for names based on Hawaiian mythology. At that time, (136108) 2003 EL61 and its two known moons were named after the deity of the island of Hawaii, where the Mauna Kea Observatory is located, in order to pay tribute to the area where these objects were discovered. Haumea is the goddess of fertility and childbirth; she had many children growing on different parts of her body. The two known moons at that time were named after Haumea's two daughters: (136108) Haumea I Hi'iaka and (136108) Haumea II Namaka. Hi'iaka is about 310 km in diameter, has an orbital period of 48.9 days, and an orbital radius of 49,900 km. The satellite Namaka turned out to be about half as small (about 170 km); it orbits Haumea in an orbit with a semi-major axis of 25.6 thousand km with a period of about 18 days. It also turned out that Haumea has a narrow ring system. Photometric observations made by Brown's group in 2005 using a telescope at the Keck Observatory revealed that Haumea rotates with a rotation period around its own axis of about 4 hours. The reason for the brightness fluctuation with an amplitude of about 0.28m may be the inhomogeneity of its surface, or an elongated shape. Simulations showed that the best fit is given by a model in the form of an ellipsoid with dimensions of 1960×1518×996 km with an average albedo of 0.73. Studies of Haumea's spectrum in the 1.0-2.4 μm range, carried out in 2005 using telescopes at the Gemini and Keck observatories, revealed that its surface is covered mainly with crystalline water ice with grains with a diameter of 25-50 μm. Such crystalline ice forms at*

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*temperatures above 110 K, while the temperature on the surface of Haumea is always below 50 K, at which only ice in an amorphous state is formed. The spectra and color of Haumea's surface indicate that this celestial object has recently undergone a "renovation" of its surface. Observations of the cover of the star by the dwarf planet Haumea on January 21, 2017, also revealed a ring around Haumea. It became the first ring discovered around a trans-Neptunian object. The ring has a radius of about 2287 km, a width of almost 70 km, and a transparency index of 0.5. It exists within the Roche limit of the dwarf planet Haumea.*

Haumea was the first of the dwarf planets [13, 14] to be discovered after the discovery of Pluto in 1930 [21]. However, its current name and formal recognition as a dwarf planet were delayed for several years due to disputes over who should be considered the discoverer of this celestial object [20]. It turned out that the object was first observed by a team from the California Institute of Technology led by Michael E. Brown. However, the very first announcement of its discovery was made by a Spanish team led by José Luis Ortiz Moreno. In this regard, priority should have belonged to the Spanish. Therefore, when registering the discovery, the object was assigned the temporary designation "2003 EL61", according to the date of the image in which the object was found by the Spanish group. However, Brown suspected the Spanish team of fraud. That is, to make their discovery, they used observations of researchers from the California Institute of Technology.

In contrast, Ortiz's team accused the American team of interfering in the work of the International Astronomical Union (IAU). And only in September 2008, the IAU officially approved the name of the celestial object Haumea, proposed by the Americans, while the Spaniards proposed calling it Ataecina. On September 17, 2008, simultaneously with the naming, Haumea was included in the newly created class of dwarf planets in 2006. Thus, it became the fifth dwarf planet and the fourth plutoid: together with Pluto, Eris and Makemake.

Haumea was first recorded back in 1955 in images obtained at the Palomar Observatory. It turned out that Michael Brown's team found this object on 12/28/2004 in images that it received on 05/06/2004 also at the Palomar Observatory using the 1.3-meter SMARTS telescope. It was immediately clear that this object could not be a large planet because it was noticeably smaller than Pluto. For this reason, Brown was in no hurry to officially announce the discovery. And this announcement was postponed for the joint announcement of several other trans-Neptunian objects (TNOs) of quite significant sizes at once. Researchers hoped to obtain additional observational data necessary to clarify their nature.

The discovery of the first satellite around Haumea allowed researchers to conclude that this object contains significantly more rocky rocks than other TNOs,

and its satellite consists mainly of ice. After obtaining such conclusions, the researchers managed to discover a whole family of TNOs with fairly close orbits. This family is the first among TNOs, which includes, in addition to Haumea and its satellites, also such objects as (55636) 2002 TX300 ( $\approx 364$  km), (24835) 1995 SM55 ( $\approx 174$  km), (19308) 1996 TO66 ( $\approx 200$  km), (120178) 2003 OP32 ( $\approx 230$  km) and (145453) 2005 RR43 ( $\approx 252$  km). This allowed to formulate the conclusion that all these TNOs could be the remains of the icy mantle of Haumea, which was once thrown out of it as a result of a collision with another trans-Neptunian object.

On the same day that the Minor Planet Center made this announcement, Brown's team also announced the discovery of another Kuiper Belt object, Eris. This object was even more distant and brighter, and probably larger than Pluto; therefore, it was submitted as the tenth planet. This announcement was made somewhat earlier than planned, in order to prevent the possibility of similar news about the discovery by other researchers. Moreover, Brown's team was informed that the data of their observations were publicly available, and therefore they understood that by that time there was already the possibility of open access to their observational data not only for Haumea [2, 3, 7], but also for Eris.

Following the International Astronomical Union's guidelines that classical Kuiper Belt objects [8] be named after mythological creatures, Brown's team submitted formal proposals for names from the Hawaiian pantheon in September 2006. At that time, the name of the object (136108) 2003 EL61 and its two already known moons was proposed to be after the deity of the island of Hawaii, where the Mauna Kea Observatory is located, in order to pay tribute to the area where the objects were discovered. Haumea is the goddess of fertility and childbirth; she had many children growing on different parts of her body.

This fact also points to a family of icy bodies that may have broken away from the dwarf planet during a very long-ago collision. Two known moons that could have formed in this way were named after Haumea's two daughters: (136108) Haumea I Hi'iaka and (136108) Haumea II Namaka. The diameter of the satellite Hi'iaka was about 310 km, its period of rotation was 48.9 days, and the radius of its orbit was 49.9 thousand km. The satellite Namaka turned out to be about half the size (about 170 km) of Hi'iaka. It orbits Haumea in an orbit with a semi-major axis of 25.6 thousand km and a period of about 18 days.

However, due to disputes over the discoverer of this celestial body, this object remained without an approved name for a long time. And only on 17.09.2008 the International Astronomical Union published data that both organizations responsible for naming dwarf planets – the Committee on Small Body Nomenclature CSBN and the Working Group on Planetary Systems Nomenclature WGPSN – agreed on the proposal proposed by Brown's team: Haumea. However,

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the date of discovery of Haumea was given as 7.03.2003, and the place of its discovery was declared the Sierra Nevada Observatory. Although, the name of the discoverer of this dwarf planet was never indicated. However, no one disputed M. Brown's authorship of the discovery of two satellites around Haumea: Hi'iaka and Namaka.

According to observational data obtained at the Palomar Observatory, this dwarf planet, plutoid or trans-Neptunian object 136108 Haumea, has a very elongated shape with dimensions of  $1,960 \times 1,518 \times 996$  km. This is smaller than the size of Pluto; its rotation period around its own axis is about 3.9155 hours. Two satellites with rotation periods of 34 and 49 Earth days revolve around the dwarf planet Haumea. It was also found that Haumea has a narrow ring system. Haumea's orbit was tracked using archival images until 1955. It turned out to be inclined to the ecliptic plane at an angle of  $28.22^\circ$ , is elongated with an eccentricity of 0.195; Haumea's maximum distance from the Sun is 51.47 AU and the minimum is 34.49 AU. That is, Haumea does not enter the orbit of the giant planet [10-12] Neptune. Haumea passed the aphelion point at the end of 1991, and now it has begun to approach the Sun. The period of rotation of Haumea around the Sun is 281.8 years. Therefore, the closest passage of perihelion will occur in 2133.

The very first photometric observations, made by Brown's group in 2005 using a telescope at the Keck Observatory, revealed that Haumea is a very unusual object. It rotates very quickly, with a period of rotation around its own axis of about 4 hours. It is believed that such a rapid rotation was caused by the impact that formed both its satellites and the entire collisional family. Such a very rapid rotation of Haumea should distort its shape. This is indirectly confirmed by the fact that it has large brightness fluctuations with an amplitude of about  $0.28^m$ . However, the cause of such fluctuations may be the heterogeneity of its surface. After all, for example, at Pluto, brightness deviations sometimes reach 35%. It is believed that for Haumea the cause of brightness changes [1, 4] may be its elongated shape. Modeling the shape of this object showed that the best fit is given by a model in the form of an ellipsoid with dimensions of  $1960 \times 1518 \times 996$  km with an average albedo value of 0.73. In this case, Haumea ranks third or fourth in size among trans-Neptunian objects after Eris, Pluto and, possibly, Makemake.

Measurements of the size of Haumea, made in 2009 using the infrared space observatory Herschel, showed that its average diameter lies in the range of  $1212 \div 1491$  km. The mass of Haumea, determined from the orbits of its satellites, is  $4.0 \times 10^{21}$  kg, which is about 24% of the mass of Eris and 32% of the mass of Pluto. Based on the calculated shape of the object, its average density was initially estimated at  $2.6\text{--}3.34$  g/cm<sup>3</sup>. By now, this value has decreased to values of  $2.5\text{--}2.6$  g/cm<sup>3</sup>.

Studies of Haumea's spectrum in the 1.0-2.4  $\mu\text{m}$  range, carried out in 2005 using telescopes at the Gemini and Keck observatories, revealed that its surface, like the surface of Charon [22], is covered mainly with water ice [17, 18] in the form of grains with a diameter of 25-50  $\mu\text{m}$ . That is, Haumea's spectrum showed features similar to the surface of Pluto's moon Charon; such characteristics indicate the possible presence of crystalline water ice on its surface. And this looks quite strange. After all, such crystalline ice is formed at temperatures higher than 110K, while the temperature on the surface of Haumea is always below 50K, at which only ice in an amorphous state is formed. In addition, the structure of crystalline ice is very unstable under the constant influence of bombardment by cosmic rays and high-energy particles from the Sun. The albedo of this dwarf planet is in the range of 0.6-0.8; and such values are also consistent with the form of crystalline ice.

However, the time scale for the transformation of the crystalline form of ice into amorphous ice under the influence of such bombardment is about ten million years [9]. While all trans-Neptunian objects have been in their current locations with low temperature values for many billions of years [23]. And their surface under the influence of such long-term radiation exposure should have long since reddened and darkened [15]. After all, on their surfaces, usually there are materials from organic ices and tholin-like compounds, as is the case, for example, in the case of Pluto [19].

Therefore, the spectra and color of the surface of Haumea indicate that members of the "family" of this celestial object should have recently undergone "renewal" of their surface. And this could lead to the formation of fresh crystalline ice. However, no plausible mechanism for the possible restoration of this surface has yet been proposed [6]. Although the spectrum of this dwarf planet still differs from the spectrum of pure ice, since it has features that can also be explained by the presence of hydrogen cyanide (up to 27%) and some phyllosilicate rocks on the surface. Also, the spectrum of Haumea shows an unusual decrease in intensity for crystalline ice after a wavelength of 2.35  $\mu\text{m}$ . This can also be explained by the presence of potassium cyanide or other carbon minerals in its snow.

In 2009, a large reddish spot was reported to be detected in the visible range on the surface of Haumea. It is believed that this may be an area of accumulation of some minerals or organic compounds, or a trace of a collision of Haumea with another celestial body.

Observations of the eclipse of the star by the dwarf planet Haumea on 21.01.2017 also revealed a ring around Haumea [5, 25]. It was the first ring [24] discovered around a trans-Neptunian object. The ring has a radius of about 2287 km, a width of almost 70 km, and a transparency index of 0.5. It exists within the Roche limit of the dwarf planet Haumea. The plane of the ring is inclined by about

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3.2° to the equatorial plane of Haumea and almost coincides with the orbital plane of Haumea's larger satellite, Hi'iaka. This ring is located close to a location with a 1:3 orbital resonance with the rotation of the dwarf planet and adds about 5% to the total brightness of Haumea.

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