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Calculating the Mass of Objects That Are Transitive from Giant Planets to Brown Dwarfs Using a New Formula for the Gravitational Potential

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Abstract: The gravitational potential characterizes the gravitational field of ordinary bodies and has dimension equal to the square of the velocity. In 2021, a new expression for the law of universal gravitation was obtained, which is completely analogous to Coulomb's law. Using this result, the presented paper introduces a new formula for the gravitational potential, which has dimension of velocity. This formula establishes a clear boundary for the mass of objects that are transitive from giant planets to stars of the smallest masses (brown dwarfs).

Keywords: giant planets; brown dwarfs; gravitational potential; gravitational constant

1. Introduction

The stars are the main elements of galaxies; compared to them, the planets have mostly much smaller masses. However, the distribution of celestial objects by mass continuously changes from giant planets to stars of the smallest masses, called *brown dwarfs*.

Mass is an important distinguishing feature of planets from stars, but there is no obvious boundary of transition between a high-mass planet and a low-mass brown dwarf. It is generally taken to be about 13 times the mass of Jupiter, after which the conditions for the start of thermonuclear fusion are reached. Numerous studies have suggested this value as the official distinction between the two types of objects. However, many scholars believe that this limit does not have any solid physical basis. Some astronomers argue that a more significant distinction between planets and brown dwarfs is their mode of formation. Therefore, there is currently no clearly accepted transition mass between giant planets and brown dwarfs.

Here we propose a theoretical method for calculating the transition mass.

2. Method

According to Newton's law of universal gravitation, the absolute value of the force of gravitational interaction between two objects is

$$F = Gm_1m_2/r^2, \quad (1)$$

where m_1 and m_2 are the masses of the objects, and r is the distance between the centers of their masses, and $G = 6.674\times10^{-11}$ m³/(kg·s²) is the gravitational constant.

From Newton's law follows the formula for the gravitational potential Φ (we mean its modulus), which characterizes the gravitational field of an ordinary body:

$$\Phi = Gm/r, \quad (2)$$

where m is the mass of a body, r is the distance from the body's center of mass to the point at which the potential is determined. Note that the gravitational potential has the dimension of the square of the velocity, $[\Phi] = [v^2] = (\text{m/s})^2$.

It should be recalled that the International System of Units (SI) is a composite system that includes, in particular, the m-kg-s system of mechanical units (MKS system) and the m-kg-s-A system

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of electromagnetic units (MKCA system). The second system differs from the first primarily in that, along with the existing three base units (meter, kilogram, and second), it has a fourth base unit – ampere (A).

For example, in the MKSA system, the elementary electric charge $e = 1.6\times10^{-19}$ C, and the proportionality coefficient, included in Coulomb's law, $k = 9\times10^{9}$ N·m²/C².

In 2018, an article [1] was published that showed that the electromagnetic units of the MKSA system (the ampere, coulomb, ohm, volt, etc.) can be converted using the base units of the MKS system: m, kg, s. In the paper, it was shown that in the MKS system

$$e = 1.6\times10^{-25}\ \text{kg·m/s}, \tag{3}$$

$$k = c^2/F_1 = 9\times10^{21}\ \text{m/kg}\ , \tag{4}$$

where $c = 3\times10^{8}$ m/s is the speed of light in vacuum, and $F_1 = 10^{-5}$ kg·m/s² (or 1 g·cm/s² – the unit of force in the CGS system).

Using these results, it was shown in paper [2] that the constant

$$G = kv_g^2, \tag{5}$$

where $v_g = (G/k)^{1/2} = 0.8617\times10^{-16}$ m/s is the *elementary speed*, i.e., the lowest speed of movement in nature.

Substituting the expression for G into equation (1), the new formula for the law of universal gravitation was obtained:

$$F = kv_g^2m_1m_2/r^2 = km_1v_g\ m_2v_g/r^2 \tag{6}$$

or

$$F = kg_1g_2/r^2, \tag{7}$$

where $g_1 = m_1v_g$ and $g_2 = m_2v_g$ are the *gravitational charges* of the interacting bodies, and the coefficient $k = 9\times10^{21}$ m/kg.

So, we obtained an expression exactly analogous to Coulomb's law (in the MKSA system):

$$F = kq_1q_2/r^2, \tag{8}$$

where F is the absolute value of the force of electrostatic interaction in a vacuum of two point electric charges q_1 и q_2, r is the distance between them, and the coefficient $k = 9\times10^{9}$ N·m²/C².

From Coulomb's law follows the electric potential φ that characterizes the electrostatic field of a point electric charge q and is defined in a vacuum by the formula

$$\varphi = kq/r, \tag{9}$$

where r is the distance from the charge to the point at which the potential is determined.

In the MKS system, the electric charge has the dimension of the momentum, $[q]$ = kg·m/s, and the coefficient k has the dimension $[k]$ = m/kg; thus, the electric potential has the dimension of velocity, $[\varphi] = [kq/r] = [v]$ = m/s.

Hence, analogous to the electric potential, we can introduce a new formula for the gravitational potential:

$$\Phi_v = kg/r = kmv_g/r, \tag{10}$$

where $g = mv_g$ is the gravitational charge of a body, r is the distance from the body's center of mass to the point at which the potential is determined, the coefficient 9×10^{21} m/kg, and the potential Φ_v has the dimension of *velocity*, $[\Phi_v] = [v]$ = m/s.

It turns out that we can use this potential to calculate the transition mass from giant planets to brown dwarfs.

As previously mentioned, when the transition mass is reached, the conditions for the start of thermonuclear fusion are formed. An object with such a mass begins to emit the light (electromagnetic waves) that can travel a distance equal to the radius of the observed universe (R).

This radius is determined by the formula $R=c/H$, where H is the Hubble constant. The exact value of this constant is not yet known; measurements give a value of $H \approx 70$ (km/s)/Mpc (1Mpc = 3.0856×10^{22} m).

Let us assume that for an object with a transition mass m, at a distance equal to the radius of the observed universe ($r=R$) the potential Φ_v is equal to the speed of light ($\Phi_v=c$). Hence, according to equation (10),

$$c = kmv_g/R. \quad (11)$$

Using the value $H = 70$ (km/s)/Mpc = 2.26×10^{-18} s^{-1}, we calculate:

$$m = cR/kv_g = c^2/Hv_g(c^2/F_1) = F_1/Hv_g \approx 5.136\times10^{28} \text{ kg} \approx 27\, M_J\,, \quad (12)$$

where $M_J = 1.9\times10^{27}$ kg is the Jupiter mass.

So, we obtained a value twice the accepted intermediate mass. Therefore, we must finally accept that for an object with an intermediate mass m_i, at a distance $r=R$ the potential $\Phi_v=c/2$:

$$c/2 = km_iv_g/R. \quad (13)$$

Hence, the intermediate mass

$$m_i = cR/2kv_g = F_1/2Hv_g = 2.568\times10^{28} \text{ кг} \approx 13.5\, M_J. \quad (14)$$

Thus, to accurately calculate the transition mass, we need to know the exact value of the Hubble constant.

3. Conclusion

There is no universally acknowledged criterion for distinguishing brown dwarfs from giant planets. Numerous studies have suggested a definition based on an object's mass, taking the ~13 Jupiter mass limit for the ignition of deuterium. Here we have presented a method for calculating the transition mass using a new formula for the gravitational potential, which has the dimension of velocity. This formula establishes a clear boundary for the transition between a giant planet and a brown dwarf: *for an object with an intermediate mass, at a distance equal to the radius of the observed universe* ($r=R$), *the potential* Φ_v *is equal to half the speed of light* ($\Phi_v=c/2$).

Competing Interests: The author declares no competing interests.

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