The Cosmic Pull: Quantifying Gravity Across Celestial Objects

Applying Newtonian Gravitation to Planetary and Stellar Systems

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Abstract: This paper explores surface gravity, the acceleration caused by gravity at the surface of a celestial body, across a wide range of objects in the universe. We first calculate the surface gravity of major planets and the Moon using Newton's law of universal gravitation, illustrating how mass and radius influence gravitational strength.These calculations are then extended to stellar objects, including red supergiants, white dwarfs, neutron stars(and pulsars), demonstrating how gravity behaves under extreme conditions. By comparing these results, we see how gravity varies across the universe and how the same simple formula can be applied to both familiar planets and rare stellar objects. This study highlights the importance of surface gravity for understanding planetary environments, stellar evolution, and the limits of gravitational physics.

Keywords: Surface gravity; Newtonian gravitation; Planetary physics; Stellar objects; Red supergiants; Extreme gravity

1 Introduction

Gravity is one of the most important forces in nature. It pulls objects toward one another, from tiny particles to massive planets. As we live on Earth, we experience it constantly because it is what keeps us stuck to the ground; without it, even a small jump would send us floating away. In the absence of gravity, planets would drift freely through space and collide with each other.

Acceleration is the rate at which an object's velocity changes over time. When we talk about gravitational acceleration, we mean how fast an object speeds up, as it falls due to gravity. The value of acceleration is approximately $9.81\,\mathrm{m/s^2}$ on Earth, meaning that each second an object falls, its velocity increases with a constant value of 9.81 meters per second. Understanding gravitational acceleration is essential not only for basic physics but also for predicting the motion of rockets, satellites, and planets. Without this concept, we could not send spacecraft to other worlds or calculate the orbits of the bodies in our solar system.

Long before researchers had a proper understanding of gravitational acceleration, many natural phenomena seemed mysterious and were hard to predict. For instance, why do objects of different weights fall at the exact same speed? And what force so precisely guides the planets around the Sun, keeping them from spiraling inward or flying off course? These questions amazed astronomers and researchers for centuries. And it was Newton in the seventeenth century who first formulated the concept of gravity as a universal force and introduced the idea of acceleration and how it influenced almost everything in this universe. Newton's law of universal gravitation describes how particles in the universe attract every other particle, with a force that depends on their weights and the distance between each object. This helped the researchers to solve the mystery of planetary motion, predict the routes of comets, and also begin the foundation for classical mechanics. Later, this concept became a must for exploring more advanced problems in physics and astronomy. By knowing how powerful gravity is on different astronomical objects, we can calculate how objects behave on the Moon, on Mars, or even on big planets like Jupiter, providing important knowledge for space exploration and understanding mysteries of the universe.

2 Surface Gravity and Its Formula

To understand how gravity varies across the solar system, we need a way to calculate the gravitational acceleration on the surface of any planet or moon. This value, denoted by g, quantifies the strength of a celestial body's gravitational pull at its surface. This knowledge is essential for planning space missions; for example, it explains why astronauts on the Moon can jump higher and determines the thrust needed for a rocket to launch from Mars. The surface gravity, g, is derived by combining Newton's second law of motion with his law of universal gravitation. The resulting formula is:

$$g = \frac{GM}{R^2} \tag{1}$$

where G is the gravitational constant ($6.6743 \times 10^{-11}\,\mathrm{N \cdot m^2/kg^2}$), M is the mass of the planetary body, and R is its radius.

This equation shows that surface gravity is directly proportional to the body's mass and inversely proportional to the square of its radius. In simpler terms, a more massive and denser planet will have a stronger surface gravity. By applying this formula, we can calculate and compare the gravitational environments of different planetary bodies, providing key insights for exploration and understanding the solar system.

3 Calculation of Surface Gravity on Celestial Bodies

Using equation (1), we can find the surface gravity of any celestial body simply by substituting the appropriate values. However, in many cases, the outcomes may differ because the values are not even fully accurate.

3.1 Surface gravity of Major Planetary Objects

In this subsection, we calculate the surface gravity of the major planetary bodies in the solar system, shown in Figure 1, including the eight planets and the Moon. We will demonstrate the calculation method using the Moon as a detailed example. The results for all other bodies will then be summarized in a comparative table.

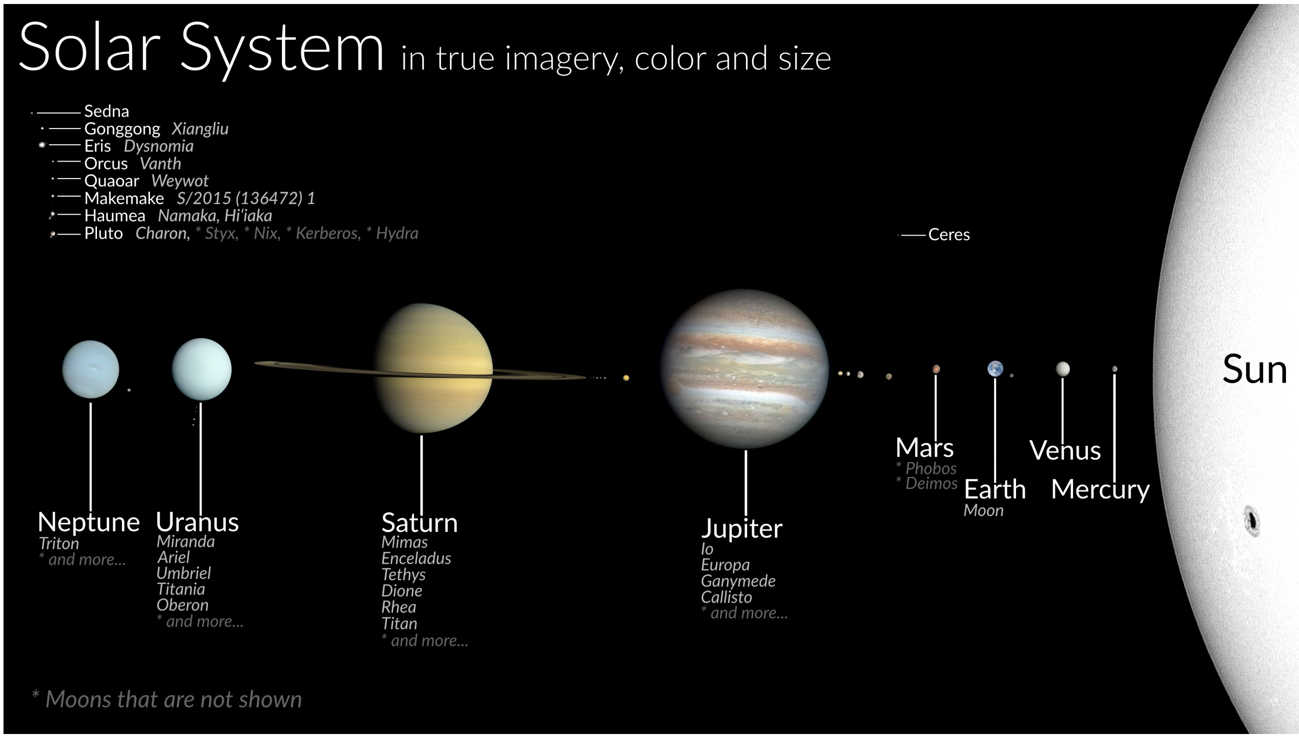

Figure 1: True-color image of the Solar System showing planets, major moons, and dwarf planets; image by CactiStaccingCrane, CC BY-SA 4.0, with planetary data from NASA, ESA, and contributors.

We know,
The mass and the radius of the Moon are respectively,
$M = 7.34767 \times 10^{22}$ kg
$R = 1.737 \times 10^{6}$ m
Gravitational constant, $6.6743 \times 10^{-11}\,\mathrm{N \cdot m^2/kg^2}$

Now let's put the values together on equation (1).

$$g = \frac{GM}{R^2} = \frac{(6.6743 \times 10^{-11})(7.34767 \times 10^{22})}{(1.737 \times 10^{6})^2} \tag{2}$$

$$g \approx 1.625383\,\mathrm{m/s^2}.$$

That means the gravitational acceleration on the surface of the moon is $g_{\text{moon}} \approx 1.62\,\mathrm{m/s^2}$.

Now let's make a table and enter the mass and radius of the planets one by one to calculate their values.

Table 1: Surface gravity of the Moon and major planets: calculated vs approximate values

Planet / Moon	**Mass M (kg)**	**Radius R (m)**	**Calculated g (m/s^2)**	**Approx. g (m/s^2)**
Moon	7.3476×10^{22}	1.7374×10^{6}	1.625383	1.62
Mercury	3.3011×10^{23}	2.4397×10^{6}	3.701617	3.70
Mars	6.4169×10^{23}	3.3895×10^{6}	3.727861	3.73
Uranus	8.6810×10^{25}	2.5559×10^{7}	8.692672	8.69
Venus	4.8673×10^{24}	6.0518×10^{6}	8.870022	8.87
Earth	5.9722×10^{24}	6.3781×10^{6}	9.798450	9.80
Saturn	5.6834×10^{26}	6.0268×10^{7}	10.44336	10.44
Neptune	1.0241×10^{26}	2.4764×10^{7}	11.14458	11.15
Jupiter	1.8982×10^{27}	7.1492×10^{7}	24.78750	24.79

From the data in the table, we can see that surface gravity depends on both the mass and the radius of a celestial body. It follows the formula

$$g = \frac{GM}{R^2}$$

This means that planets with more mass, like Jupiter, have a stronger surface gravity than smaller ones such as the Moon or Mercury. Jupiter is a gas giant and does not have a solid surface. Its gravity is about $24.79\,\text{m/s}^2$ at a certain level in its atmosphere. This is around 2.5 times stronger than Earth's gravity. So, if a person could jump 50 centimeters high on Earth, they would only be able to jump about 20 centimeters on Jupiter, if they could even stand there.

The table also shows a big difference between Earth ($g \approx 9.8\,\text{m/s}^2$) and the Moon ($g \approx 1.62\,\text{m/s}^2$). The Moon's gravity is about one sixth of Earth's, which is why astronauts could jump higher and move more slowly there. Knowing how surface gravity changes from one planet to another also helps scientists find the escape velocity, which is the speed needed to leave a planet's gravity. This idea is very important for space travel and sending spacecraft away from Earth.

3.2 Surface gravity of Stellar objects

Having calculated the surface gravity for planetary bodies within the solar system, we now extend this analysis to a broader range of celestial objects, including other stars. This will give us a clearer understanding of how interesting this simple topic can become. We can obtain these values using the same formula and then organize them in a table for better visualization.

However, for stellar objects that are very far from us, it is difficult to get perfectly accurate values, so many of our results will be approximate. Also, some of these calculations will include the symbols $M_\odot$ and $R_\odot$, which are units of mass and radius used in stellar and galactic astronomy. It represents the mass and radius of the Sun and is equal to:

$$M_\odot = 1.9884 \times 10^{30} \text{ kg and } R_\odot = 6.957 \times 10^{8} \text{ m}$$

3.2.1 Surface gravity of KW Sagittarii

KW Sagittarii is a red supergiant star in the constellation Sagittarius. It is one of the largest stars known, with a radius over 1,000 times that of the Sun. Its cool surface temperature results in its deep red color. Like other red supergiants, it generates energy by fusing heavier elements in its core as it nears the end of its life. This enormous size and brightness make it a classic example of a star in its late evolutionary stages, and it is expected to end its life in a supernova explosion.

The mass of KW Sagittarii is estimated to be between $20\,M_\odot$ and $40\,M_\odot$. To convert these values into kilograms, we simply multiply by the mass of the Sun. For Calculations we are assuming that the star is not rotating.

The calculations for the minimum(($20\,M_\odot$) and maximum estimated masses ($40\,M_\odot$) are:

$$20 \times (1.9884 \times 10^{30} \text{ kg}) \approx 3.9768 \times 10^{31} \text{ kg and } 40 \times (1.9884 \times 10^{30} \text{ kg}) \approx 7.9536 \times 10^{31} \text{ kg}$$

To find a reasonable single value for the mass of KW Sagittarii, we take the midpoint of the estimated range from $20\,M_\odot$ to $40\,M_\odot$ and convert that into kilograms:

$$M_{\text{avg}} = \frac{20\,M_\odot + 40\,M_\odot}{2} = 30\,M_\odot \approx 5.9652 \times 10^{31} kg \tag{3}$$

The star's radius is estimated to be 1009 ± 142 times the radius of the Sun ($R_\odot$). Using the average value of $1009R_\odot$, we calculate the approximate radius in meters as:

$$R = 1009 \times R_\odot = 1009 \times 6.957 \times 10^{8} \text{ m} \approx 7.019613 \times 10^{11} \text{ m}.$$

The mass and radius of the star are therefore:

$$M_{\text{KW Sagittarii}} \approx 5.9652 \times 10^{31} \text{ kg} \quad (\text{for } 30M_\odot), \quad R_{\text{KW Sagittarii}} \approx 7.019613 \times 10^{11} \text{ m}.$$

Using the formula for surface gravity, we have:

$$g_{\text{KW Sagittarii}} = \frac{GM_{\text{KW Sagittarii}}}{R^2_{\text{KW Sagittarii}}} = \frac{(6.6743 \times 10^{-11})(5.9652 \times 10^{31})}{(7.019613 \times 10^{11})^2} \tag{4}$$

$$\therefore \; g_{\text{KW Sagittarii}} \approx 0.0080798 \text{ m/s}^2.$$

3.2.2 Surface gravity Betelgeuse (Red Supergiant)

It is a massive red supergiant in its final stages of life. Located about 700 light-years away in the constellation Orion, it has used the hydrogen in its core and now burns heavier elements. This late evolutionary phase is marked by its immense size, which is more than 1,000 times the Sun's radius, and powerful stellar winds that eject a vast cloud of gas and dust. Betelgeuse loses a lot of material through strong stellar winds, creating a surrounding cloud of gas and dust. One day, it will explode as a supernova, briefly shining brighter than many other stars in the sky.

$$M_{\text{Betelgeuse}} = 16.5\, M_\odot \approx 3.28086 \times 10^{31} \text{ kg},$$
$$R_{\text{Betelgeuse}} = 764\, R_\odot \approx 5.315148 \times 10^{11} \text{ m}.$$

$$g = \frac{GM_{\text{Betelgeuse}}}{R^2_{\text{Betelgeuse}}} = \frac{(6.6743 \times 10^{-11})(3.28086 \times 10^{31})}{(5.315148 \times 10^{11})^2} \tag{5}$$

$$\therefore \; g_{\text{Betelgeuse}} \approx 0.007751 \text{ m/s}^2.$$

3.2.3 Surface gravity of Proxima Centauri

It was discovered in 1915 by Robert Innes. Its name comes from Latin. "Proxima" means nearest, and "Centauri" shows it is part of the Alpha Centauri system. At that time, it was considered to be the closest star to the Sun, and even today modern tools for astronomy also proved that it is still the closest known star, about 4.24 light-years away. It is a small red dwarf, much cooler and dimmer than the Sun. Despite its size, it is very interesting because it is part of a three-star system with Alpha Centauri A and B. It has at least one planet in its habitable zone, where liquid water could exist.

Proxima Centauri is also an active star, producing strong solar flares that can affect its planets. Its closeness to Earth makes it a key target for astronomers who want to study nearby stars and exoplanets. It helps researchers understand how stars and planets can form and evolve. One day, it might even be a target for future space missions.

$$M_{\text{Proxima Centauri}} = 0.1221\, M_\odot \approx 2.42783 \times 10^{29} \text{ kg},$$
$$R_{\text{Proxima Centauri}} = 0.1542\, R_\odot \approx 1.072769 \times 10^{8} \text{ m}.$$

$$g = \frac{GM_{\text{Proxima Centauri}}}{R^2_{\text{Proxima Centauri}}} = \frac{(6.6743 \times 10^{-11})(2.42783 \times 10^{29})}{(1.072769 \times 10^{8})^2} \tag{6}$$

$$\therefore \; g_{\text{Proxima Centauri}} \approx 1408.028894 \text{ m/s}^2.$$

3.2.4 Surface gravity of the Sun

The Sun is at the center of our solar system and is essential for life on Earth. It is the main source of light and energy for our planet. The Sun is mostly made of hydrogen (70%) and helium (28%), with small amounts of other elements. In its core, it produces energy through nuclear fusion, turning hydrogen into helium and releasing huge amounts of heat and light. This energy drives Earth's climate, affects the weather, and powers photosynthesis, allowing plants to make food and supporting all life on Earth.

It has a diameter of about 1.4 million kilometers, which is roughly 109 times wider than Earth. Its gravity keeps all the planets, moons, and other objects in the solar system in orbit, which is a really interesting fact. The surface of the Sun, called the photosphere, has a temperature of about 5,500 degrees Celsius, while its core reaches around 15 million degrees Celsius. The Sun also produces solar winds, streams of charged particles that shape space weather and can cause auroras on Earth. It is currently a middle-aged star, around 4.6 billion years old, and is expected to keep shining for another 5 billion years before evolving into a red giant.

$$M_{\text{Sun}} \approx 1.9884 \times 10^{30} \text{ kg},$$
$$R_{\text{Sun}} \approx 6.957 \times 10^{8} \text{ m}.$$

$$g = \frac{GM_{\text{Sun}}}{R_{\text{Sun}}^2} = \frac{(6.6743 \times 10^{-11})(1.9884 \times 10^{30})}{(6.957 \times 10^{8})^2} \tag{7}$$

$$\therefore\ g_{\text{Sun}} \approx 274.1987 \text{ m/s}^2.$$

3.2.5 Surface gravity of Sirius A

Sirius A is the brightest star in the night sky and the main star of the Sirius system, located in the constellation Canis Major. It is about twice as massive as the Sun and is mostly made of hydrogen and helium. Sirius A shines with a white-blue color. In its core, it produces huge amounts of energy through nuclear fusion, turning hydrogen into helium. Its brightness and energy make it one of the most visible and prominent stars from Earth.

$$M_{\text{Sirius A}} = 2.063\, M_{\odot} \approx 4.1020692 \times 10^{30} \text{ kg},$$
$$R_{\text{Sirius A}} = 1.711\, R_{\odot} \approx 1.19034 \times 10^{9} \text{ m}.$$

$$g = \frac{GM_{\text{Sirius A}}}{R_{\text{Sirius A}}^2} = \frac{(6.6743 \times 10^{-11})(4.1020692 \times 10^{30})}{(1.19034 \times 10^{9})^2} \tag{8}$$

$$\therefore\ g_{\text{Sirius A}} \approx 193.226 \text{ m/s}^2.$$

3.2.6 Surface gravity of Sirius B

Sirius B is the smaller companion of Sirius A in the Sirius star system, located in the constellation Canis Major. It is a white dwarf, which means it is the remnant of a star that has used up its fuel. Even though it is very small, about the size of Earth, it is extremely dense. Its mass is similar to the Sun, but all that mass is packed into a tiny space.

Sirius B no longer produces energy through fusion. It slowly cools over time, but it is still very hot, with a surface temperature over 25,000 degrees Celsius. Because of its faint light compared to Sirius A, it is much harder to see with the naked eye. Sirius B is one of the closest white dwarfs to Earth and has been an important object for astronomers studying the life cycle of stars.

$$M_{\text{Sirius B}} = 1.018\, M_{\odot} \approx 2.02419 \times 10^{30} \text{ kg},$$
$$R_{\text{Sirius B}} = 0.0084\, R_{\odot} \approx 5.8428 \times 10^{6} \text{ m}.$$

$$g = \frac{GM_{\text{Sirius B}}}{R_{\text{Sirius B}}^2} = \frac{(6.6743 \times 10^{-11})(2.02419 \times 10^{30})}{(5.8428 \times 10^{6})^2} \tag{9}$$

$$\therefore\ g_{\text{Sirius B}} \approx 3.957 \times 10^{6} \text{ m/s}^2.$$

3.2.7 Surface gravity of a Neutron Star

A neutron star is what remains after a massive star explodes in a supernova. During the explosion, the outer layers of the star are blown away, and its core collapses under its own gravity. This collapse compresses the core into an extremely small sphere, only about 10 to 20 kilometers across, yet containing more mass than the Sun. Neutron stars are made almost entirely of neutrons, which makes them incredibly dense. Their gravity is extremely strong, far stronger than anything we experience on Earth. Some neutron stars spin very fast, sometimes hundreds of times per second, sending out beams of radiation. When these beams sweep past Earth, we detect them as pulses of light and radio waves, and such stars are called pulsars. Despite their small size, neutron stars are extremely hot and can shine brightly for millions of years. They are among the most fascinating and extreme objects in the universe, showing what happens when matter is pushed to its limits.

One well-known example is the Vela Pulsar, located in the constellation Vela. It was formed from a supernova explosion, leaving behind a dense core only about 20 kilometers wide, yet with more mass than the Sun. The Vela Pulsar spins about 11 times every second, sending out beams of light and radio waves that we detect as regular pulses. Its gravity is so strong that it can bend space and affect nearby matter, and its rapid spin makes it one of the most extreme neutron stars known. Scientists study it to understand the physics of matter under extreme conditions and to explore the forces and energy that shape our universe. Despite its tiny size, the Vela Pulsar stands out as a striking example of the power of neutron stars.

$$M_{\text{Vela Pulsar}} = 1.35\, M_{\odot} \approx 2.68434 \times 10^{30} \text{ kg},$$
$$R_{\text{Vela Pulsar}} \approx 9.656 \times 10^{3} \text{ m}.$$

$$g = \frac{GM_{\text{Vela Pulsar}}}{R^2_{\text{Vela Pulsar}}} = \frac{(6.6743 \times 10^{-11})(2.68434 \times 10^{30})}{(9.656 \times 10^{3})^2} \tag{10}$$

$$\therefore\ g_{\text{Vela Pulsar}} \approx 1.92153 \times 10^{12} \text{ m/s}^2.$$

3.3 Analysis of Gravitational Acceleration Among Different Celestial Bodies

Table 2: Calculated and Approximate Surface Gravity Values for Selected Celestial Bodies

Planet / Moon	**Mass M (kg)**	**Radius R (m)**	**Calculated g (m/s^2)**	**Approx. g (m/s^2)**
Betelgeuse	3.2808×10^{31}	5.3151×10^{11}	0.007751	0.0076
KW Sagittarii	5.9652×10^{31}	7.0196×10^{11}	0.008079	0.0080
Moon	7.3476×10^{22}	1.7374×10^{6}	1.625383	1.62
Mercury	3.3011×10^{23}	2.4397×10^{6}	3.701617	3.70
Mars	6.4169×10^{23}	3.3895×10^{6}	3.727861	3.73
Uranus	8.6810×10^{25}	2.5559×10^{7}	8.869267	8.86
Venus	4.8673×10^{24}	6.0518×10^{6}	8.870022	8.87
Earth	5.9722×10^{24}	6.3781×10^{6}	9.798450	9.80
Saturn	5.6834×10^{26}	6.0268×10^{7}	10.44336	10.44
Neptune	1.0241×10^{26}	2.4764×10^{7}	11.14458	11.15
Jupiter	1.8982×10^{27}	7.1492×10^{7}	24.78750	24.79
Sirius A	4.1020×10^{30}	1.1903×10^{7}	193.22636	193
Sun	1.9884×10^{30}	6.957×10^{8}	274.19871	274
Proxima Centauri	2.4278×10^{29}	1.0727×10^{8}	1408.02889	1408
Sirius B	2.0241×10^{30}	5.8428×10^{6}	3.957×10^{6}	3.95×10^{6}
Vela Pulsar	2.6843×10^{30}	9.6560×10^{3}	1.92153×10^{12}	1.92×10^{12}

From this table, it is quite clear that among all the planetary objects we chose to calculate gravity for, the red supergiant Betelgeuse has the lowest surface gravity. It is so weak that we would not even feel any pull if we were standing on its surface. KW Sagittarii has almost the same gravity as Betelgeuse. Interestingly, Mercury and Mars also have nearly equal surface gravity, even though their masses and radii are completely different.

Other celestial bodies show a significant amount of gravitational pull, but for Sirius B and the Vela Pulsar, the surface gravity is truly enormous. Despite KW Sagittarii and Betelgeuse being much more massive and larger in size than the Vela Pulsar, the pulsar still has the strongest gravitational pull. This clearly demonstrates that gravity depends on both an object's mass and radius, and it can vary widely from one celestial body to another — something we can clearly observe from this table.

4 Limitations and Refinements

We should remember that the surface gravity values calculated earlier are only rough estimates. In those calculations, we assumed that each planet or moon is a perfect sphere with mass evenly distributed. In reality, celestial bodies have mountains, valleys, oceans, and uneven mass distributions, which can slightly affect gravity at different locations. Additionally, we used average masses and radii for stars and planets, so the actual surface gravity may vary depending on the values used. For example, we assumed the radius of Betelgeuse is $764\,R_{\odot}$, but the exact value is uncertain because these stars are extremely distant. Some rotate rapidly, and others cannot be directly observed even with telescopes. Astronomers determine masses and radii using indirect methods, so different values will yield slightly different surface gravity results, though all will be close to the estimated values.

Another factor that affects surface gravity is the planet's spin. A spinning planet creates a force that slightly reduces gravity at the equator. We can account for this with the formula:

$$g_{\text{eff}} = \frac{GM}{R^2} - \omega^2 R \cos^2 \theta \tag{11}$$

Here, g_{eff} is the effective gravity at latitude θ, M is the mass of the planet, R is the radius, and ω is the planet's rotation speed. At the equator, $\theta = 0°$, so it becomes:

$$g_{\text{equator}} = \frac{GM}{R^2} - \omega^2 R \tag{12}$$

For example, for Earth ($M = 5.97 \times 10^{24}$ kg, $R = 6.37 \times 10^6$ m, $\omega = 7.29 \times 10^{-5}$ rad/s), we get:

$$g_{\text{Earth, equator}} = \frac{(6.6743 \times 10^{-11})(5.9722 \times 10^{24})}{(6.3781 \times 10^6)^2} - (7.29 \times 10^{-5})^2(6.3781 \times 10^6) \tag{13}$$

$$\therefore g_{\text{Earth, equator}} \approx 9.78\,\text{m/s}^2$$

This is a bit lower than the standard $9.81\,\text{m/s}^2$ because Earth's spin slightly reduces gravity at the equator.

We can use this adjustment for other planets and moons too, to get a more accurate value for surface gravity across the solar system.

5 Conclusion

From the massive red supergiants to the tiniest planets, gravity connects every corner of the universe. The perfect paths along which all planets, comets, and other celestial objects move in the universe exist because of gravity. It is like the thread that ties everything together, keeping order in a place that could have easily been pure chaos. Every step we take, every object that stays where it is, happens because gravity is holding it all in balance. Without it, nothing would stay close. The oceans would drift away, the air would escape, and we ourselves would float endlessly through space. Gravity is something we often forget to notice because it is always around us, quietly doing its job. Yet when we look deeper, we realize how powerful it truly is. It keeps galaxies spinning, stars shining, and planets moving in perfect harmony. It gives shape to everything we see. And even though gravity holds us down, it also challenges us to rise above it. When we send rockets into space, we are not just escaping Earth — we are fighting one of the strongest forces in nature. It reminds us how small we are, but also how determined we can be. Gravity is not just a force; it is a reminder of connection, of balance, and of how beautifully the universe works together to make everything possible.

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