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P3_7 Why Does Venus Spin Backwards?

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Abstract

Venus has a very slow, retrograde rotation compared to the 24 hour prograde rotations of Earth and Mars. We find that for an impacting asteroid to have changed Venus' rotation from an Earth-like period and direction to its current state, a minimum asteroid mass of $2 \times 10^{29} kg$ would be required, and that such a collision would destroy Venus. This makes it unlikely that such a collision is responsible for the odd Venusian rotation.

Introduction

All planets in the solar system orbit in an anticlockwise direction when viewed from the solar north pole, and all but one rotate anticlockwise about their rotational axis too. This is called prograde motion, meaning the motion is in the same direction as the Sun's rotation. Venus is this exception to the rule. Whilst both Mars and the Earth maintain a prograde rotation with a period of roughly 24 hours, Venus rotates once every 243 Earth days in the retrograde direction [1].

As Venus should have formed from the same material at around the same time as the other inner planets, it could have had a similar rotational period to begin with. We model the mass and energy of an asteroid impact powerful enough to change the rotational period from that of the Earth's to that of Venus, in the other direction. Such a collision could hypothetically explain why Venus' rotation is so different, provided the impact isn't so energetic it breaks the planet apart.

Theory

In order to calculate the energy and mass of the impactor, we must consider the change in angular momentum required to reverse the rotation direction. The rotational angular momentum for a sphere is given by the following equation [2]:

$$L = \frac{4\pi M_p R_p^2}{5P},\qquad(1)$$

where M_p and R_p are the mass and radius of the sphere (planet) respectively, and P is the rotation period. For Venus we take $M = 4.87 \times 10^{24}$ kg and $R = 6052$ km [1] By substituting in 243 days, and 1 day into this equation, we find that the change in angular momentum is 5.72×10^{33} $kgm^{-2}s^{-1}$ in order to change the rotation from Earth-like to Venus-like.

We now consider how angle of impact will affect the transfer of momentum. If we define θ as the angle between the impact and the surface of the planet then the momentum transfer in any impact is given by

$$p = Mv cos\theta,\qquad(2)$$

where M and v are the mass and velocity of the impacting body. In order to reverse the rotation of the planet, the momentum transferred must equal the change in angular momentum required, found in Eq. (1). Equating these gives the following relation for impactor mass:

$$M = \frac{\Delta L}{v cos\theta}.\qquad(3)$$

Note that we assume the transfer is 100% efficient, and only consider impacts in the plane of rotation. We take the value of impactor velocity, $v = 25 kms^{-1}$[3]. Hence, we can plot impactor mass as a function of angle, shown in Figure 1. Even at the minimum angle, the impactor mass is over $2 \times 10^{29} kg$, more massive than Jupiter. Using this mass, and the aforementioned velocity, this corresponds to an impact energy of $7.2 \times 10^{37} J$.
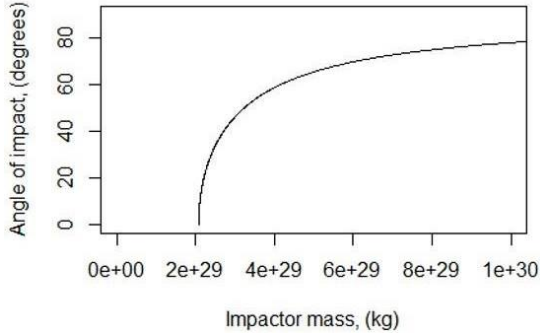

Figure 1: Required impactor mass as a function of angle of impact

The gravitational binding energy of a spherical body [2] is given as

$$U = \frac{3GM_p^2}{5R_p}. \qquad (4)$$

Substituting the values of mass and radius for Venus [1], we get a binding energy of $1.6 \times 10^{32} J$. This is far less than even the kinetic energy for the minimum possible mass, so any collision of this scale would destroy the planet.

Discussion

Given that any collision with enough energy to change the rotational direction of the planet would destroy the planet, this cannot be the cause of the retrograde rotation. .

Our model assumes that Venus originally had a rotational rate similar to the Earth's, but it may have had a slower rotational period due to spin-orbit resonance, similar to Mercury. This is when the rotational and orbital period are in a ratio of low integers (in the case of Mercury, 3:2 [4]). This would mean a far less energetic impact would be required to produce its rotational rate, and due to the young surface of Venus, an impact crater may not be seen.

A more probable solution to this problem comes from the idea that tidal effects from other planets caused the rotation of Venus to change in the past. Atmospheric effects may have caused the planet to flip on its axis, in a similar manner to the magnetic poles on Earth [5]. Either of these theories explain the strange rotation in a more believable manner than the massive impactor scenario.

Taking this work further, the core accretion mechanism of planetary formation could be considered. If two planetesimals in the solar system's early history came together in a particular way, their resultant rotation could be retrograde. Advanced modelling of this scenario is beyond the scope of this work, however.

Conclusions

We find that in order to change the rotation of Venus from an Earth-like rotation to its current rotation, the minimum mass of an impactor travelling at the average speed of asteroids would need to be $2 \times 10^{29} kg$. This gives an impactor kinetic energy of $7.2 \times 10^{37} J$, whereas Venus has a gravitational binding energy of $1.6 \times 10^{32} J$. Thus, such an impact would not change the direction of rotation, but rather completely destroy the planet.

References

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[4] (Elkins-Tanton, L. (2011). Uranus, Neptune, Pluto, and the outer solar system. New York: Facts on File.)

[5] https://www.scientificamerican.com/article/why-venus-spins-the-wrong/ [Accessed 16 November 2017]