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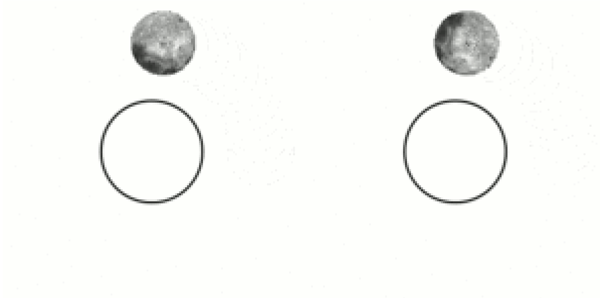
Tidal locking

Tidal locking (also called **gravitational locking** or **captured rotation**) occurs when the long-term interaction between a pair of co-orbiting astronomical bodies drives the rotation rates into a harmonic ratio with the orbital period. This effect arises from the gravitational gradient (tidal force) between the co-orbiting bodies, acting over a sufficiently long period of time. Once tidal locking is achieved for one of the bodies, there is no more net transfer of angular momentum between the two objects, although there can be some back and forth transfer over the course of an orbit. In the special case where the orbital eccentricity is nearly zero, tidal locking results in one hemisphere of the revolving object constantly facing its partner, an effect known as **synchronous rotation**.[1][2] For example, the same side of the Moon always faces the Earth, although there is some libration because the Moon's orbit is not perfectly circular. A tidally locked body in synchronous rotation takes just as long to rotate around its own axis as it does to revolve around its partner.



Tidal locking results in the Moon rotating about its axis in about the same time it takes to orbit Earth. Except for libration effects, this results in the Moon keeping the same face turned toward Earth, as seen in the left figure. (The Moon is shown in polar view, and is not drawn to scale.) If the Moon were not rotating at all, it would alternately show its near and far sides to Earth, while moving around Earth in orbit, as shown in the right figure.

Usually, only the satellite is tidally locked to the larger body.[3] However, if both the mass difference between the two bodies and the distance between them are relatively small, each may be tidally locked to the other; this is the case for Pluto and Charon.

This effect is employed to stabilize some artificial satellites.

One form of hypothetical tidal locked planets are eyeball planets, that in turn are divided into "hot" and "cold" eyeball planets.[4]

Contents

Mechanism

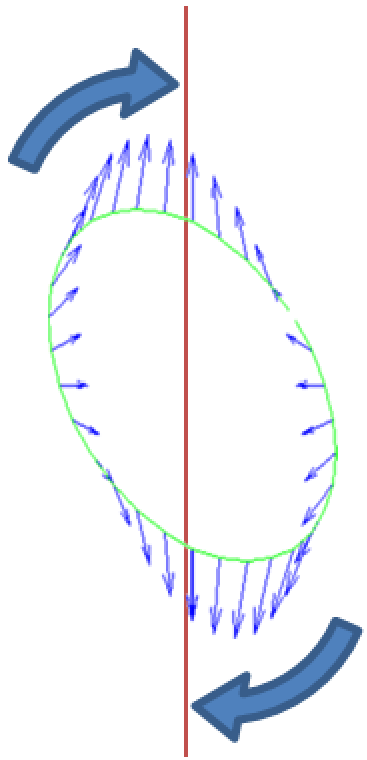
The change in rotation rate necessary to tidally lock a body B to a larger body A is caused by the torque applied by A's gravity on bulges it has induced on B by tidal forces.

The gravity of body A produces a tidal force on B that distorts its gravitational equilibrium shape slightly so that it becomes elongated along the axis oriented toward A, and conversely, is slightly reduced in dimension in directions orthogonal to this axis. These distortions are known as tidal bulges. When B is not yet tidally locked, the bulges travel over its surface, with one of the two "high" tidal bulges traveling close to the point where body A is overhead. For large astronomical bodies that are nearly spherical due to self-gravitation, the tidal distortion produces a slightly prolate spheroid, i.e. an axially symmetric ellipsoid that is elongated along its major axis. Smaller bodies also experience distortion, but this distortion is less regular.

The material of B exerts resistance to this periodic reshaping caused by the tidal force. In effect, some time is required to reshape B to the gravitational equilibrium shape, by which time the forming bulges have already been carried some distance away from the A–B axis by B's rotation. Seen from a vantage point in space, the points of maximum bulge extension are displaced from the axis oriented toward A. If B's rotation period is shorter than its orbital period, the bulges are carried forward of the axis oriented toward A in the direction of rotation, whereas if B's rotation period is longer, the bulges instead lag behind.

Because the bulges are now displaced from the A–B axis, A's gravitational pull on the mass in them exerts a torque on B. The torque on the A-facing bulge acts to bring B's rotation in line with its orbital period, whereas the "back" bulge, which faces away from A, acts in the opposite sense. However, the bulge on the A-facing side is closer to A than the back bulge by a distance of approximately B's diameter, and so experiences a slightly stronger gravitational force and torque. The net resulting torque from both bulges, then, is always in the direction that acts to synchronize B's rotation with its orbital period, leading eventually to tidal locking.

Orbital changes



If the tidal bulges on a body (green) are misaligned with the major axis (red), the tidal forces (blue) exert a net torque on that body that twists the body toward the direction of realignment

The angular momentum of the whole A–B system is conserved in this process, so that when B slows down and loses rotational angular momentum, its *orbital* angular momentum is boosted by a similar amount (there are also some smaller effects on A's rotation). This results in a raising of B's orbit about A in tandem with its rotational slowdown. For the other case where B starts off rotating too slowly, tidal locking both speeds up its rotation, and *lowers* its orbit.

Locking of the larger body

The tidal locking effect is also experienced by the larger body A, but at a slower rate because B's gravitational effect is weaker due to B's smaller mass. For example, Earth's rotation is gradually being slowed by the Moon, by an amount that becomes noticeable over geological time as revealed in the fossil record.[5] Current estimations are that this (together with the tidal influence of the Sun) has helped lengthen the Earth day from about 6 hours to the current 24 hours. Currently, atomic clocks show that Earth's day lengthens by about 15 microseconds every year.[6] Given enough time, this would create a mutual tidal locking between Earth and the Moon, where the length of a day has increased and the length of a lunar month has shortened until the two are the same. However, Earth is not expected to become tidally locked to the Moon before the Sun becomes a red giant and engulfs Earth and the Moon.[7][8]

For bodies of similar size the effect may be of comparable size for both, and both may become tidally locked to each other on a much shorter timescale. An example is the dwarf planet Pluto and its satellite Charon. They have already reached a state where Charon is only visible from one hemisphere of Pluto and vice versa. Pluto is roughly the same age as the planets in the Solar System.

Rotation–orbit resonance

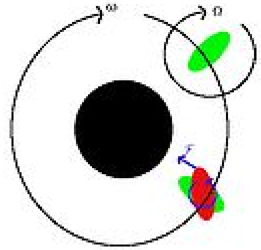
Finally, in some cases where the orbit is eccentric and the tidal effect is relatively weak, the smaller body may end up in a so-called *spin-orbit resonance*, rather than being tidally locked. Here, the ratio of the rotation period of a body to its own orbital period is some simple fraction different from 1:1. A well known case is the rotation of Mercury, which is locked to its own orbit around the Sun in a 3:2 resonance.

Many exoplanets (especially the close-in ones) are expected to be in spin–orbit resonances higher than 1:1. A Mercury-like terrestrial planet can, for example, become captured in a 3:2, 2:1, or 5:2 spin-orbit resonance, with the probability of each being dependent on the orbital eccentricity.[9]

Occurrence

Moons

Most major moons in the Solar System – the gravitationally rounded satellites – are tidally locked with their primaries, because they orbit very closely and tidal force increases rapidly (as a cubic function) with decreasing distance.[10] Notable exceptions are the irregular outer satellites of the gas giants, which orbit much farther away than the large well-known moons.



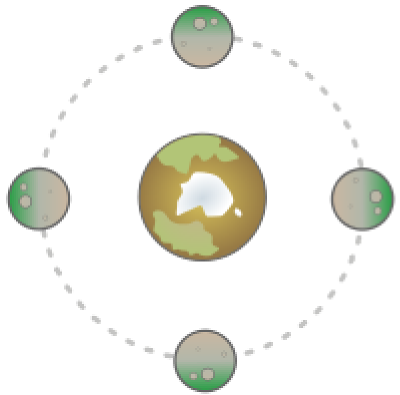
If rotational frequency is larger than orbital frequency, a small torque counteracting the rotation arises, eventually locking the frequencies (situation depicted in green)

Pluto and Charon are an extreme example of a tidal lock. Charon is a relatively large moon in comparison to its primary and also has a very close orbit. This results in Pluto and Charon being mutually tidally locked. Pluto's other moons are not tidally locked; Styx, Nix, Kerberos, and Hydra all rotate chaotically due to the influence of Charon.

The tidal locking situation for asteroid moons is largely unknown, but closely orbiting binaries are expected to be tidally locked, as well as contact binaries.

The Moon

The Moon's rotation and orbital periods are tidally locked with each other, so no matter when the Moon is observed from Earth the same hemisphere of the Moon is always seen. The far side of the Moon was not seen until 1959, when photographs of most of the far side were transmitted from the Soviet spacecraft Luna 3.[11]



Due to tidal locking, the inhabitants of the central body will never be able to see the satellite's green area.

When the Earth is observed from the moon, the Earth does not appear to translate across the sky but appears to remain in the same place, rotating on its own axis.

Despite the Moon's rotational and orbital periods being exactly locked, about 59% of the Moon's total surface may be seen with repeated observations from Earth due to the phenomena of libration and parallax. Librations are primarily caused by the Moon's varying orbital speed due to the eccentricity of its orbit: this allows up to about 6° more along its perimeter to be seen from Earth. Parallax is a geometric effect: at the surface of Earth we are offset from the line through the centers of Earth and Moon, and because of this we can observe a bit (about 1°) more around the side of the Moon when it is on our local horizon.

Planets

It was thought for some time that Mercury was in synchronous rotation with the Sun. This was because whenever Mercury was best placed for observation, the same side faced inward. Radar observations in 1965 demonstrated instead that Mercury has a 3:2 spin–orbit resonance, rotating three times for every two revolutions around the Sun, which results in the same positioning at those observation points. Modeling has demonstrated that Mercury was captured into the 3:2 spin–orbit state very early in its history, within 20 (and more likely even 10) million years after its formation.[12]

Venus's 583.92-day interval between successive close approaches to Earth is equal to 5.001444 Venusian solar days, making approximately the same face visible from Earth at each close approach. Whether this relationship arose by chance or is the result of some kind of tidal locking with Earth is unknown.[13]

Proxima Centauri b, the "Earth-like planet" discovered in 2016 that orbits around the star Proxima Centauri is tidally locked, either in synchronized rotation,[14] or otherwise expresses a 3:2 spin-orbit resonance like that of Mercury.[15]

Because the Moon is 1:1 tidally locked, only one side is visible from Earth.

Stars

Close binary stars throughout the universe are expected to be tidally locked with each other, and extrasolar planets that have been found to orbit their primaries extremely closely are also thought to be tidally locked to them. An unusual example, confirmed by MOST, is Tau Boötis, a star tidally locked by a planet. The tidal locking is almost certainly mutual.[16]

Timescale

An estimate of the time for a body to become tidally locked can be obtained using the following formula:[17]

$$t_{\text{lock}} \approx \frac{\omega a^6 I Q}{3 G m_p^2 k_2 R^5}$$

where

- ω is the initial spin rate expressed in radians per second,
- a is the semi-major axis of the motion of the satellite around the planet (given by the average of the periapsis and apoapsis distances),
- $I \approx 0.4 m_s R^2$ is the moment of inertia of the satellite, where m_s is the mass of the satellite and R is the mean radius of the satellite,
- Q is the dissipation function of the satellite,
- G is the gravitational constant,
- m_p is the mass of the planet, and
- k_2 is the tidal Love number of the satellite.

Q and k_2 are generally very poorly known except for the Moon, which has $k_2/Q = 0.0011$. For a really rough estimate it is common to take $Q \approx 100$ (perhaps conservatively, giving overestimated locking times), and

$$k_2 \approx \frac{1.5}{1 + \frac{19\mu}{2\rho g R}},$$

where

- ρ is the density of the satellite
- $g \approx Gm_s/R^2$ is the surface gravity of the satellite
- μ is the rigidity of the satellite. This can be roughly taken as 3×10^{10} N·m^{-2} for rocky objects and 4×10^9 N·m^{-2} for icy ones.

Even knowing the size and density of the satellite leaves many parameters that must be estimated (especially ω, Q, and μ), so that any calculated locking times obtained are expected to be inaccurate, even to factors of ten. Further, during the tidal locking phase the semi-major axis a may have been significantly different from that observed nowadays due to subsequent tidal acceleration, and the locking time is extremely sensitive to this value.

Because the uncertainty is so high, the above formulas can be simplified to give a somewhat less cumbersome one. By assuming that the satellite is spherical, $k_2 \ll 1, Q = 100$, and it is sensible to guess one revolution every 12 hours in the initial non-locked state (most asteroids have rotational periods between about 2 hours and about 2 days)

$$t_{\text{lock}} \approx 6\,\frac{a^6 R\mu}{m_s m_p^2} \times 10^{10}\ \text{years},$$

with masses in kilograms, distances in meters, and μ in newtons per meter squared; μ can be roughly taken as 3×10^{10} N·m^{-2} for rocky objects and 4×10^9 N·m^{-2} for icy ones.

There is an extremely strong dependence on semi-major axis a.

For the locking of a primary body to its satellite as in the case of Pluto, the satellite and primary body parameters can be swapped.

One conclusion is that, *other things being equal* (such as Q and μ), a large moon will lock faster than a smaller moon at the same orbital distance from the planet because m_s grows as the cube of the satellite radius R. A possible example of this is in the Saturn system, where Hyperion is not tidally locked, whereas the larger Iapetus, which orbits at a greater distance, is. However, this is not clear cut because Hyperion also experiences strong driving from the nearby Titan, which forces its rotation to be chaotic.

The above formulae for the timescale of locking may be off by orders of magnitude, because they ignore the frequency dependence of k_2/Q. More importantly, they may be inapplicable to viscous binaries (double stars, or double asteroids that are rubble), because the spin–orbit dynamics of such bodies is defined mainly by their viscosity, not rigidity.[18]

List of known tidally locked bodies

Solar System

Parent body	Tidally-locked satellites[19]
Sun	Mercury[20][21][12] (3:2 spin-orbit resonance)
Earth	Moon
Mars	Phobos[22] · Deimos[23]
Jupiter	Metis · Adrastea · Amalthea · Thebe · Io · Europa · Ganymede · Callisto
Saturn	Pan · Atlas · Prometheus · Pandora · Epimetheus · Janus · Mimas · Enceladus · Telesto · Tethys · Calypso · Dione · Rhea · Titan · Iapetus
Uranus	Miranda · Ariel · Umbriel · Titania · Oberon
Neptune	Proteus · Triton[22]
Pluto	Charon (Pluto is itself locked to Charon)

Extra-solar

- Tau Boötis is known to be locked to the close-orbiting giant planet Tau Boötis b.[16]

Bodies likely to be locked

Solar System

Based on comparison between the likely time needed to lock a body to its primary, and the time it has been in its present orbit (comparable with the age of the Solar System for most planetary moons), a number of moons are thought to be locked. However their rotations are not known or not known enough. These are:

Probably locked to Saturn

- Daphnis
- Aegaeon
- Methone
- Anthe
- Pallene
- Helene
- Polydeuces

Probably locked to Uranus

- Cordelia
- Ophelia
- Bianca

- Cressida
- Desdemona
- Juliet
- Portia
- Rosalind
- Cupid
- Belinda
- Perdita
- Puck
- Mab

Probably locked to Neptune

- Naiad
- Thalassa
- Despina
- Galatea
- Larissa

Extrasolar

- Gliese 581c,[24] Gliese 581g,[25][26] Gliese 581b, and Gliese 581e may be tidally locked to their parent star Gliese 581. Gliese 581d is almost certainly captured either into the 2:1 or the 3:2 spin–orbit resonance with the same star.[27]
- All planets in the TRAPPIST-1 system are likely to be tidally locked.[28][29]

See also

- Gravity-gradient stabilization
- Orbital resonance
- Planetary habitability
- Tidal acceleration
- Synchronous orbit

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