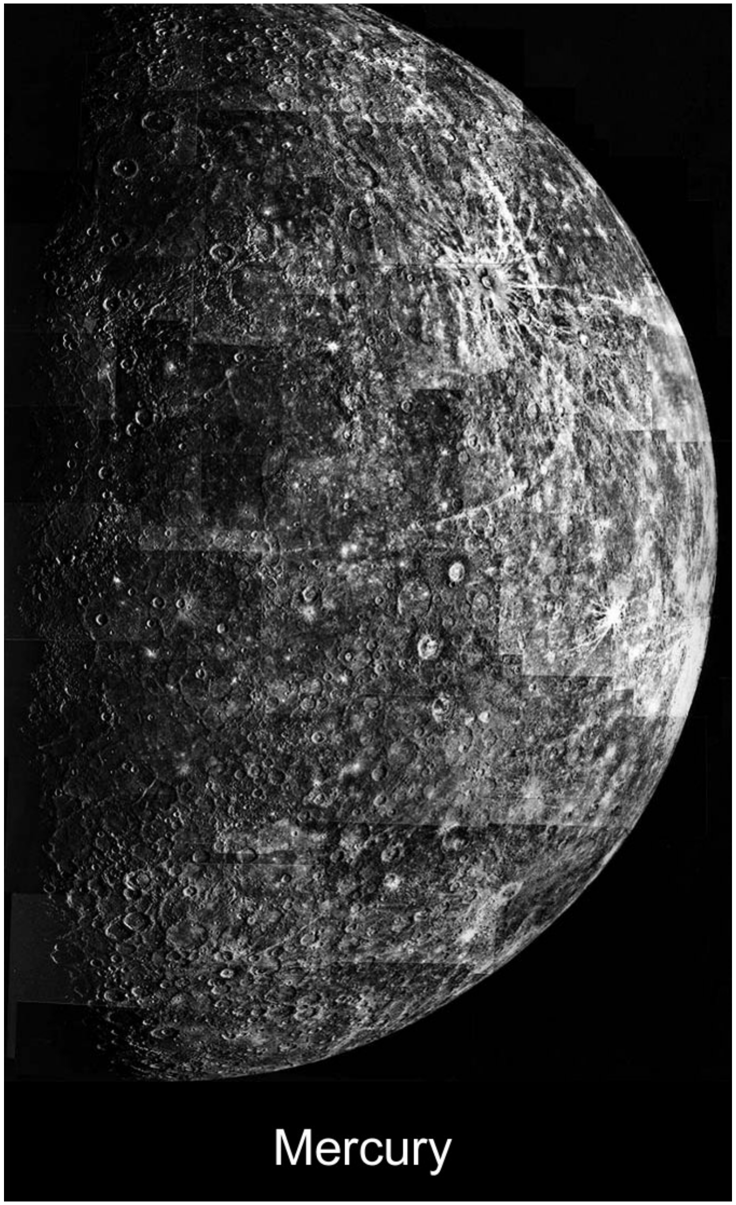

The rotation of Mercury from Schiaparelli to Colombo

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Schiaparelli and his legacy, on the centenary of his death

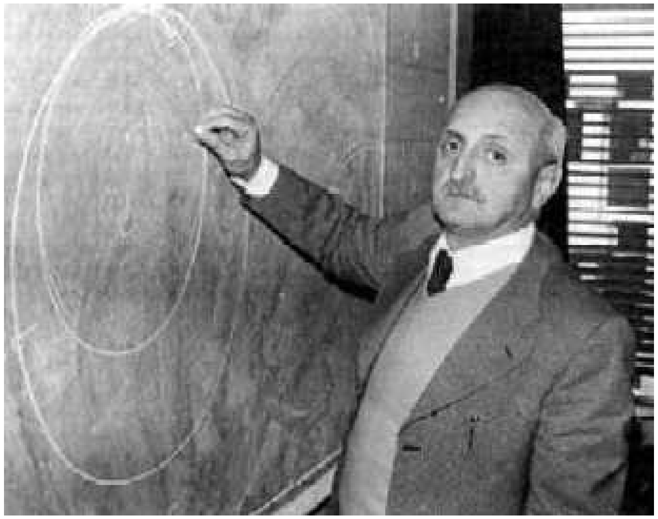
Brera October 20, 2010

UNIVERSITÀ DI PISA

Schiaparelli and Colombo: two true scientists

The way Schiaparelli and Colombo investigated the puzzle of Mercury’s rotation is amazingly similar – despite more than 80 years separation in time and a huge technological gap

They are both extremely rigorous and open minded scientists, prepared to overthrow well established views which most scientists of their times accepted with no criticism….



Mercury's rotation before Schiaparelli

Because of Mercury's small size, low reflectivity and proximity to the Sun, its markings are very difficult to observe telescopically and are even more difficult to photograph…

Schroeter in **1803** inferred from his optical observations that the rotation period was close to 24 hr period.

In **1813** the mathematician Bessel analyzed Schroeter's drawings and deduced a rotation period of 24hr 0m 53s, with the rotation axis inclined by 70° to the orbital plane

Although many astronomers remained skeptical, many found it especially appealing, aesthetically, to think of Mercury, like Mars, as having approximately the same length of day as the Earth…

This ''fact'' was not finally discredited till **1889,** when Schiaparelli published the results of his observations of Mercury…

Schiaparelli's observations of Mercury

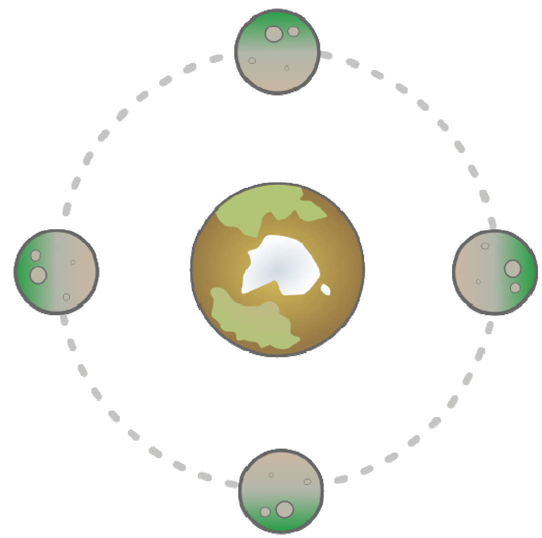
1881-1883 with small 22 cm telescope, 150 drawings

1886: new 49 cm refractor used for confirmation of previous observations

Observations covered an entire synodic period of Mercury (116 d) with only 2 breaks at inferior and superior conjunction. Unlike his predecessors, he observed Mercury not only at regular 24hr intervals but at intervals much larger or much smaller than 24hr, which allowed him to distinguish the slow rotation case

1889: publication of the results – Schiaparelli concluded that the rotation of Mercury was uniform with a period equal to the orbital one of 88 days

1889: results published (Schiaparelli Astr. Nach. 1889) – He concluded that the rotation of Mercury was uniform with a period equal to the orbital one of 88 days (The low precision of the observations did not allow Schiaparelli to determine reliably the direction of the rotation axis)

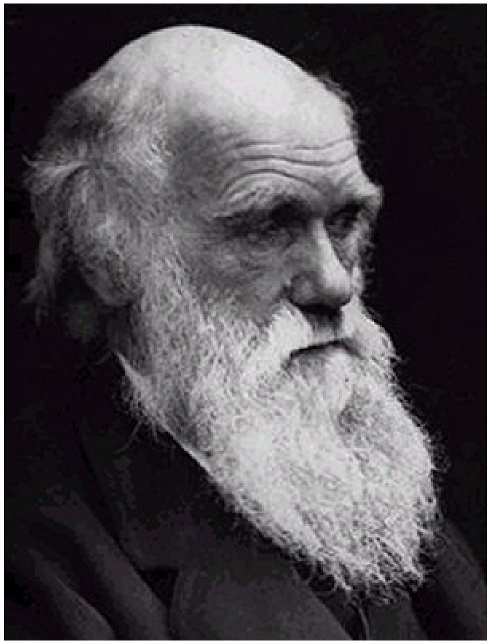


Sketch showing a case of synchronous rotation, or 1:1 resonance between the spin period and the orbital one (**like the Moon).** Mercury is different due to the very large 0.2 eccentricity…

Where does the synchronous rotation come from? (I)

Only the center of mass of an orbiting body is a zero force point (perfect equilibrium between gravitational and centrifugal force) – since the gravitational field is non uniform (and so is most of times also the centrifugal field…), any other point of the body is subject to a small force relative to its center of mass: this is called **tidal force** (because it is indeed the force responsible of tides as we know them…)

A master on tides is George H Darwin (con of Charles – below) and contemporary of Schiaparelli (1845-1912)



Where does the synchronous rotation come from? (II)

$$\text{tidal force (per unit mass)} \propto \frac{\text{radius of body}}{(\text{orbital radius})^3}$$

From G. Darwin's book "THE TIDES"

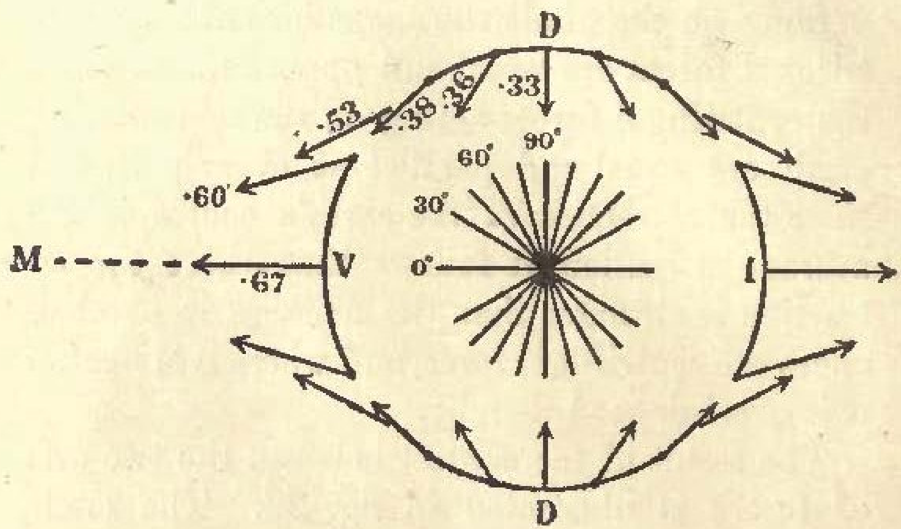


FIG. 22.—TIDE-GENERATING FORCE

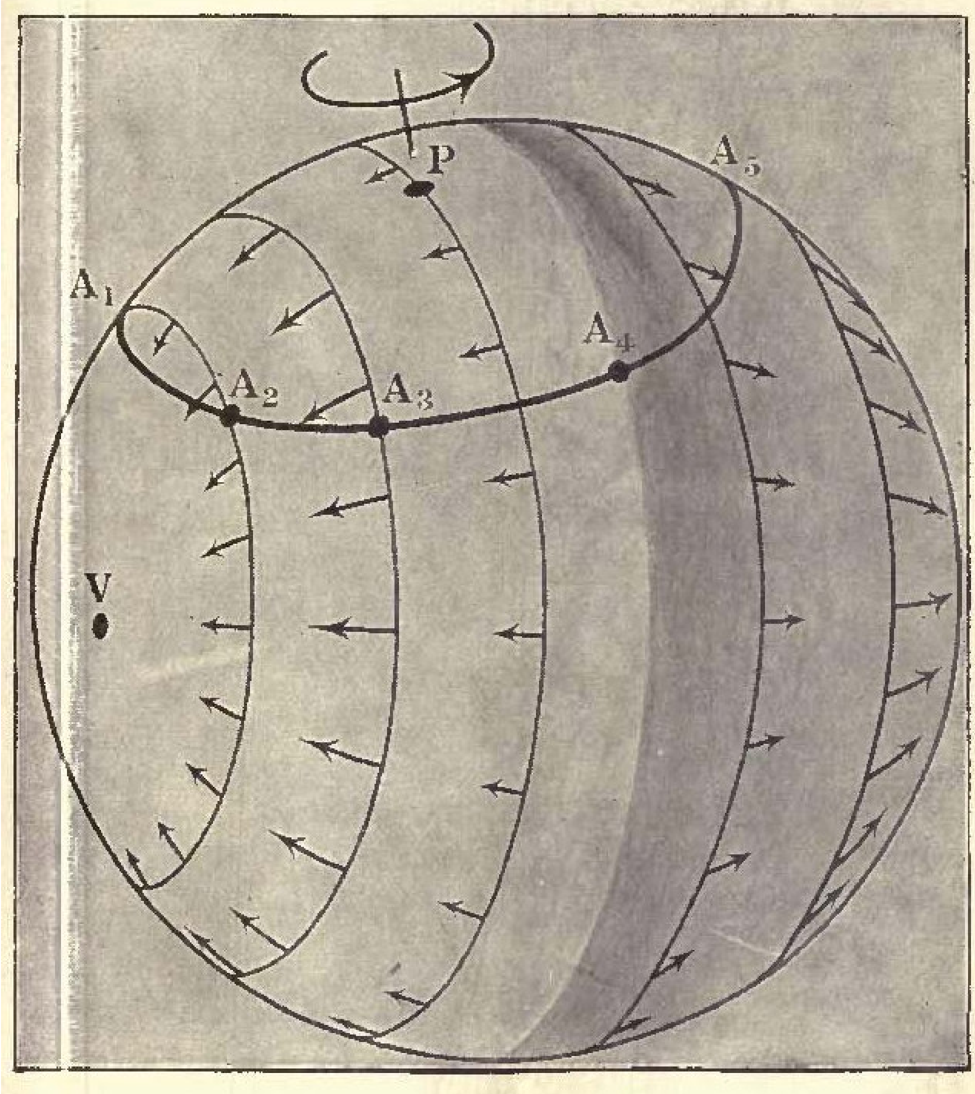


FIG. 23.—HORIZONTAL TIDE-GENERATING FORCE

Where does the synchronous rotation come from? (III)

Tidal friction: if the body's rotation is faster than the revolution, tidal bulges are carried forward by friction, thus generating a torque which slows down the rotation of the body and (by conservation of the total angular momentum) increases the orbital radius. This tidal evolution stops once the rotation and orbital period equal each other

This happened to the Moon (by the Earth) and was likely to have happened to Mercury (by the Sun)

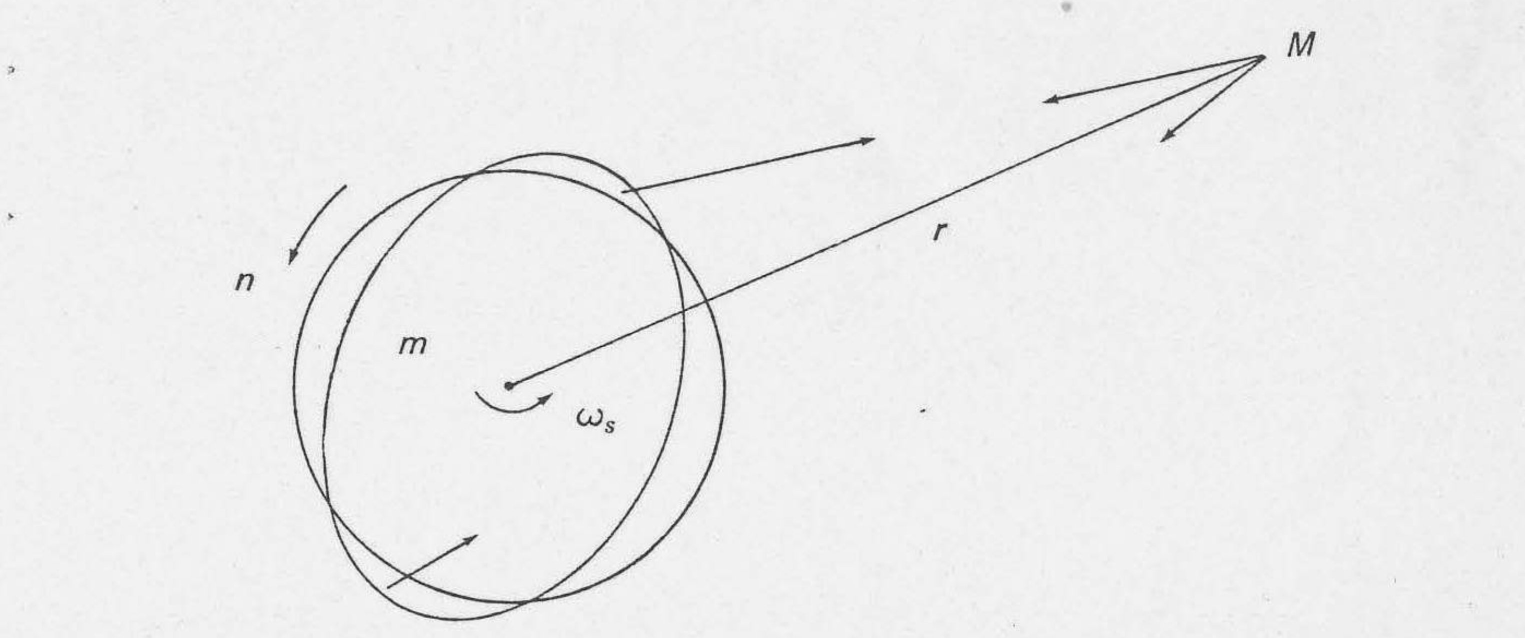


Fig. 1. M and m are the masses of planet and satellite, r is the distance between their centers, ω_s is the spin angular velocity of the satellite, n the orbital angular velocity. The plane of the sheet is the orbital plane. The figure is not on scale.

$$tidal\ friction\ torque \propto \frac{1}{Q}\frac{(radius\ of\ body)^5}{(orbital\ radius)^6}$$

George H Darwin on Schiaparelli (I)

THE TIDES

AND KINDRED PHENOMENA IN THE SOLAR SYSTEM

THE SUBSTANCE OF LECTURES DELIVERED IN 1897 AT THE LOWELL INSTITUTE, BOSTON, MASSACHUSETTS

BY

GEORGE HOWARD DARWIN

PLUMIAN PROFESSOR AND FELLOW OF TRINITY COLLEGE IN THE UNIVERSITY OF CAMBRIDGE

BOSTON AND NEW YORK
HOUGHTON, MIFFLIN AND COMPANY
The Riverside Press, Cambridge
1899

George H Darwin on Schiaparelli (I)

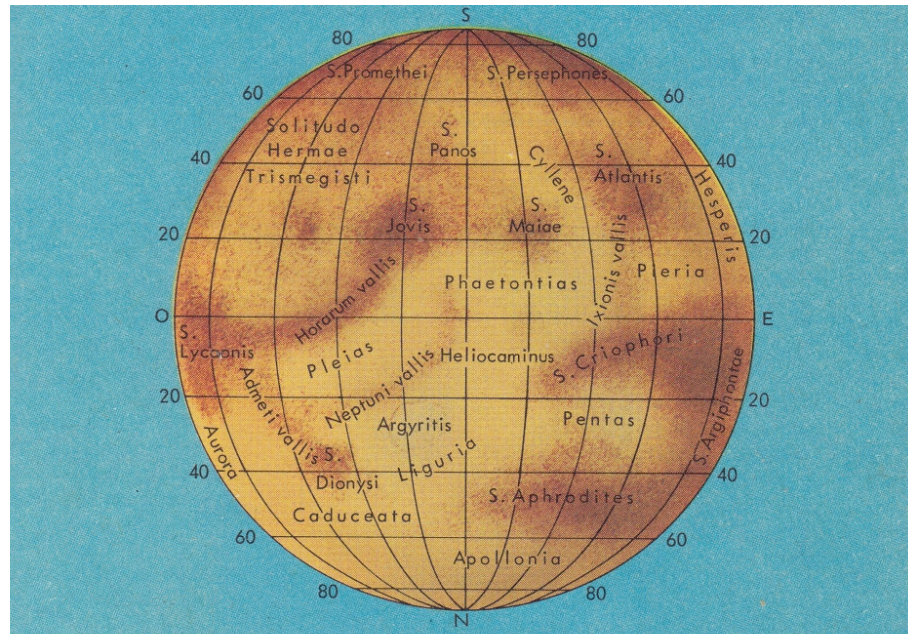
The proximity of the planets Mercury and Venus to the sun should obviously render solar tidal friction far more effective than with us. The determination of the periods of rotation of these planets thus becomes a matter of much interest. But the markings on their disks are so obscure that the rates of their rotations have remained under discussion for many years. Until recently the prevailing opinion was that in both cases the day was of nearly the same length as ours; but a few years ago Schiaparelli of Milan, an observer endowed with extraordinary acuteness of vision, announced as the result of his observations that both Mercury and Venus rotate only once in their respective years, and that each of them constantly presents the same face to the sun.

Confirmation of Schiaparelli's conclusion from the 1880's till the 1960's

In 1889 Schiaparelli successfully exploded the myth of Mercury's rapid rotation ….from then onward, till the spring of 1965 all observations were interpreted as being consistent with the 88 day rotational period he published in 1889 !!!

Danjon (1924)

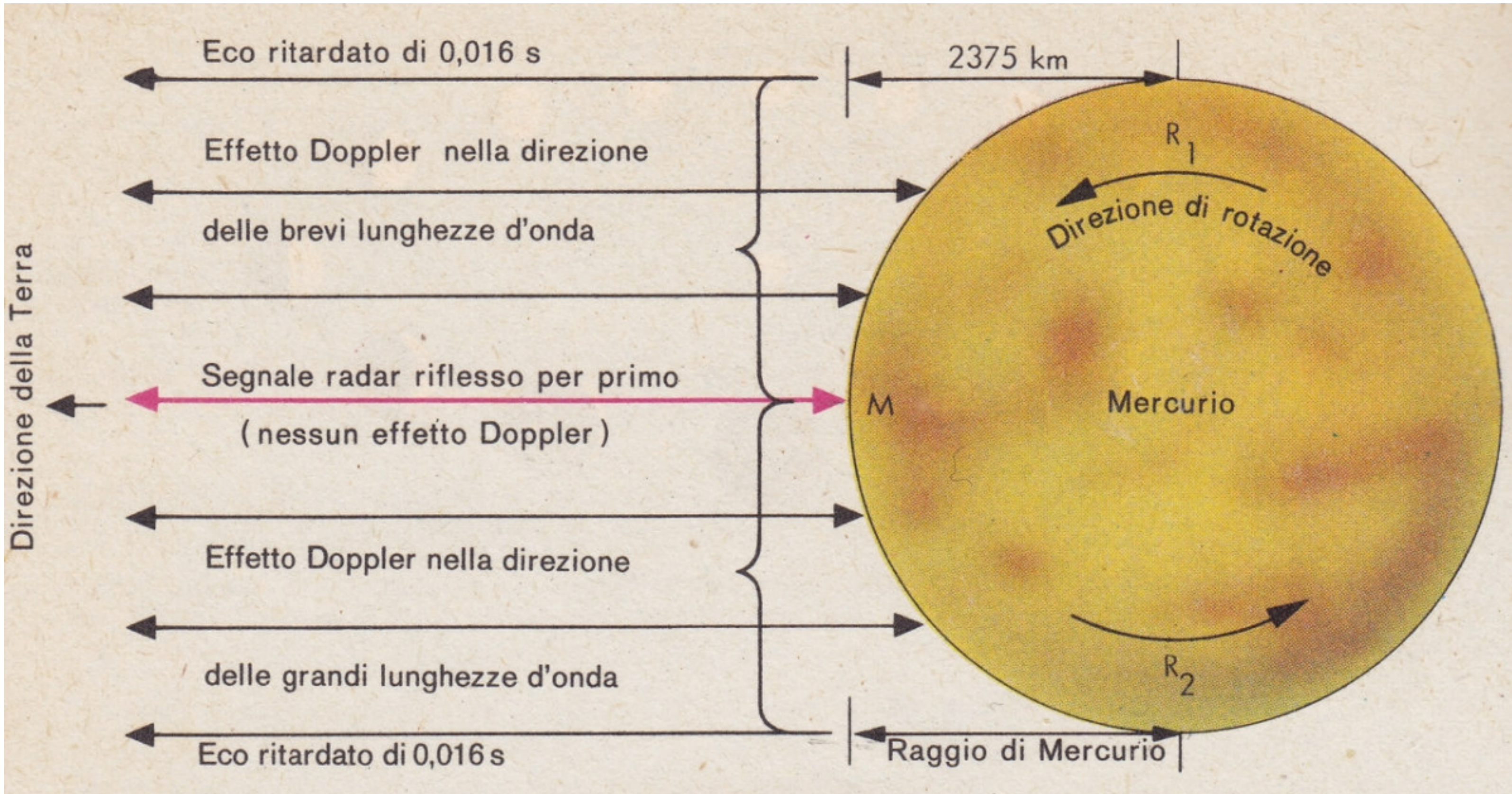
Antoniadi (1934)



B) La «classica» mappa di Mercurio, di E.M. Antoniadi (1924 - 29) con i nomi delle singole formazioni superficiali

Dollfus (1953): comparing Schiaparelli's map with his own concluded that Merucry's rotational period equaled its orbital one "with a precision greater than 1 part in 10000" … with very pure arguments…

Radar measurements of Mercury rotation in 1965



A) **Osservazioni radar di un pianeta** (per esempio Mercurio). La stazione radar riceve dapprima il segnale riflesso dalla parte centrale del pianeta, poi dai suoi bordi, con un ritardo corrispondente al doppio del raggio del pianeta; questi ultimi segnali sono inoltre affetti da effetto Doppler, da cui si può dedurre la velocità di rotazione del pianeta

The rotational period of Mercury as determined from radar Doppler-spread measurements was found to be 59 +/- 5 days (Pettingill & Dyce, Nature 1965) !!

ASTROPHYSICS

Rotational Period of the Planet Mercury

In a recent communication by S. J. Peale and T. Gold[1] the rotational period of Mercury, determined from radar Doppler-spread measurements to be 59 ± 5 days[2], has been explained in terms of a solar tidal torque effect, taking into account the large eccentricity of Mercury's orbit, and the $1/r^6$ dependence of the tidal friction (r being the Sun–planet distance). They conclude from a very brief discussion that after slowing down from a higher direct angular velocity, the planet will have a final period of rotation between 56 and 88 days, depending on the assumed form of the dissipation function. However, from their discussion it is by no means clear why permanent deformations would imply a period of 88 days as a final rotation state after a slowing-down process. A very nearly uniform rotational motion of 58·65 sidereal-day period, that is 2/3 of the orbital period, may indeed be a stable periodic solution. This rotational motion could have the axis of minimum moments of inertia nearly aligned with the Sun–Mercury radius vector at every perihelion passage. The orbital angular velocity at perihelion ($2\pi/56{\cdot}6$ days) is close to $2\pi/58{\cdot}65$ days, leading to an approximate alignment of the axis of minimum moment of inertia with the radius vector in an arc around perihelion where the interaction is strongest. The axial asymmetry of Mercury's inertia ellipsoid may result in a torque that counterbalances the tidal torque, giving a stable motion with this orientation and with a period two-thirds of the orbital period. It would therefore be possible for Mercury to have a higher permanent rigidity than that permitted by Peale and Gold.

In discussion with I. I. Shapiro[3], we concluded that the actual rotational motion may have evolved via a speeding-up process from a lower angular velocity or possibly from a retrograde motion. We would point out that a 58·65-day period, precisely because it is 2/3 of the orbital period, fits some of the old optical observations as well as the recent radar measurements.

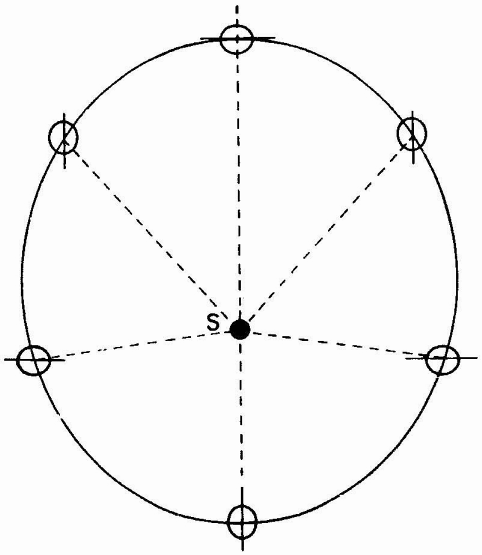


Fig. 1

In Fig. 1 a rough planar sketch is shown of the orientation of Mercury's axis of minimum moment of inertia, at different points along its orbit, given that the rotational period is two-thirds of the orbital period and that this axis is aligned with the Sun–planet vector at perihelion.

G. Colombo

University of Padova, Italy, and
Smithsonian Astrophysical Observatory,
Cambridge,
Massachusetts.

[1] Peale, S. J., and Gold, T., *Nature*, **206**, 1241 (1965).
[2] Pettingill, G. H., and Dyce, R. B., *Nature*, **206**, 1240 (1965).
[3] Shapiro, I. I. (personal communication).

Colombo's bright idea

Mercury is locked in the 3:2 (not 1:1) spin orbit resonance, hence its period 58.65 days (consistent with 59 +/- 5 days radar measurements) due to the combination of two torques from the Sun: a tidal torque and torque due to a permanent dipole-like deformation

Schiaparelli's optical observations were reanalyzed (together with Shapiro) --those over short periods– but the quality was not good enough to reliably infer the 58.65 rotation period

(Nature, November 6, 1965)

Mercury's capture into the 3/2 spin-orbit resonance as a result of its chaotic dynamics

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Mercury is locked into a 3/2 spin-orbit resonance where it rotates three times on its axis for every two orbits around the sun[1–3]. The stability of this equilibrium state is well established[4–6], but our understanding of how this state initially arose remains unsatisfactory. Unless one uses an unrealistic tidal model with constant torques (which cannot account for the observed damping of the libration of the planet) the computed probability of capture into 3/2 resonance is very low (about 7 per cent)[5]. This led to the proposal that core–mantle friction may have increased the capture probability, but such a process requires very specific values of the core viscosity[7,8]. Here we show that the chaotic evolution of Mercury's orbit can drive its eccentricity beyond 0.325 during the planet's history, which very efficiently leads to its capture into the 3/2 resonance. In our numerical integrations of 1,000 orbits of Mercury over 4 Gyr, capture into the 3/2 spin-orbit resonant state was the most probable final outcome of the planet's evolution, occurring 55.4 per cent of the time.

But is that the end of the story on the rotation of Mercury? (I)

But is that the end of the story on the rotation of Mercury? (II)

Tidal dissipation will drive the rotation rate of the planet towards a limit equilibrium value $x_1(e)n$ depending on the eccentricity e and on the mean motion n (see Methods). In a circular orbit ($e = 0$) this equilibrium coincides with synchronization ($x_1(0) = 1$), but $x_1(e_0) = 1.25685$ for the present value of Mercury's eccentricity ($e_0 = 0.206$), while the equilibrium rotation rate $3n/2$ is achieved for $e_{3/2} = 0.284927$. In their seminal work[5], Goldreich and Peale assumed that Mercury passed through the 3/2 resonance during its initial spin-down. They derived an analytical estimate of the capture probability into the 3/2 resonance and found $P_{3/2} = 6.7\%$ for the eccentricity e_0. With the updated value of the momentum of inertia[9] $(B - A)/C \simeq 1.2 \times 10^{-4}$, this probability increases to 7.73%, and our numerical simulations with the same setting give $P_{3/2} = 7.10\%$ with satisfactory agreement.

In fact, using the present value of the eccentricity of Mercury is questionable, as the eccentricity undergoes strong variations in time, owing to planetary secular perturbations. Assuming a random date for the crossing of the 3/2 resonance for 2,000 orbits, we found numerically $P_{3/2}^{BVW50} = 3.92\%$ and $P_{3/2}^{BRE74} = 5.48\%$ for these-cular (averaged) solutions of Brouwer and Van Woerkom[10] and Bretagnon[11]. It should be stressed that with the regular quasiperiodic solutions BVW50 or BRE74, as for the fixed value of the eccentricity e_0, the 3/2 resonance can be crossed only once, because $e < e_{3/2}$. This will no longer be the case with a complete solution for Mercury's orbit that takes into account its chaotic evolution[12,13]. In this case, Mercury's eccentricity can exceed the characteristic value $e_{3/2}$ (Fig. 1), and additional capture into resonance can occur.

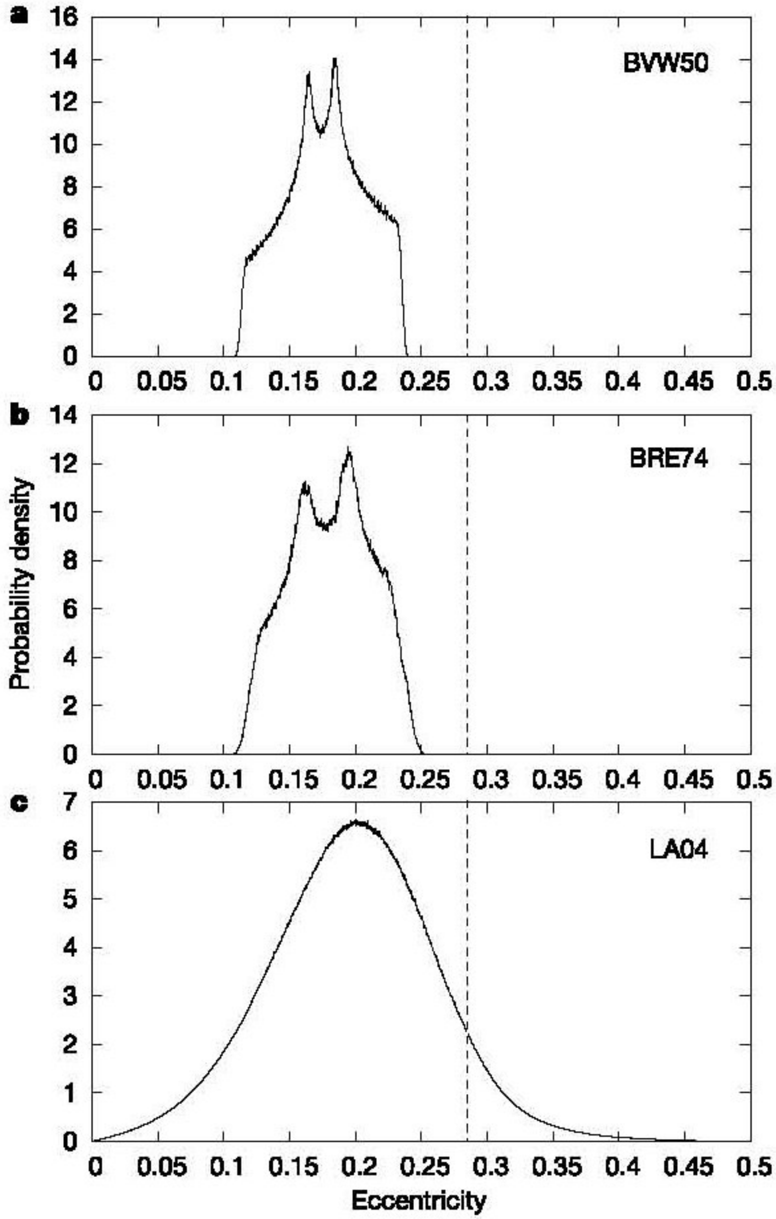

Figure 1 Probability density function of Mercury's eccentricity. Values are computed over 4 Gyr for the two quasiperiodic solutions BVW50 (ref. 10) (**a**) and BRE74 (ref. 11) (**b**) and for the numerical integration of the secular equations of refs 12 and 14 for 1,000 close initial conditions (LA04, **c**). The mean values of the eccentricity in these solutions are respectively $\bar{e}_{BVW50} = 0.177$, $\bar{e}_{BRE74} = 0.181$, and $\bar{e}_{LA04} = 0.198$. The vertical dotted line is the characteristic value $e_{3/2}$.

But is that the end of the story on the rotation of Mercury? (III)

So, Colombo's idea is right but chaos is pivotal in getting Mercury trapped in the 3:2 resonance he proposed!

Solar system chaos: a 1989 view

Solar System Chaos

We have no quarrel with Richard A. Kerr's statement (Research News, 14 Apr., p. 144) that, as faster computers have allowed longer numerical integrations, chaos is turning up everywhere in the solar system. However, the true meaning of this chaos is not yet understood. Nor is it clear how relevant it is in shaping the present configuration of our solar system; certainly chaos is not a deus ex machina capable of explaining the entire distribution of objects in the solar system.

In a few cases the results on chaos in the solar system do explain observations. For example, chaos is thought to produce the gap in the distribution of asteroids at the 3:1 orbital resonance with Jupiter by inducing highly eccentric orbits (*1*), in one case even elongated enough to cross Earth's path, thereby indicating a route for the delivery of meteorites (*2*). Close encounters with Jupiter resulting from chaos also appear to be the explanation for the drop of asteroid number density in the outer belt (*3*). Finally, the clearest example concerns Hyperion, the hamburger-shaped Saturnian satellite that is locked in orbital resonance with neighboring massive Titan inside a small libration island surrounded by a large chaotic region (*4*). It appears that, as the satellite was battered by primordial impacts, chaos prevented fragments from being reaccreted. Consequently, only Hyperion's craggy core remains today (*5*), and its very irregular shape—together with the large eccentricity forced by Titan—is responsible for the satellite's chaotic tumbling (*6*). From orbital chaos, spin chaos was born!

The presence of chaos, however, does not necessarily imply that real objects are invariably absent. Project SPACEGUARD (*7*), which investigated all known planet-crossing asteroids as influenced by all planets but Mercury and Pluto, shows that, over the 200,000-year span of the calculation, asteroid motions are highly chaotic; yet the objects are there. Moreover, chaos can mean quite different things: asteroids can be perturbed onto comet-like paths or have their eccentricities pumped up to Earth-crossing values while in orbital resonances with Jupiter, but they can also be protected from close planetary approaches.

As Kerr describes, even planetary orbits are now seen to be chaotic with the time scales for the onset of chaos being remarkably brief: 5 million years for the inner planets and 20 million years for Pluto. This chaos has startled celestial mechanicians who, for over two centuries, have been trying to prove just the opposite, namely that the solar system is stable, perhaps motivated by the simple fact that we are here. However, N-body systems with $N > 2$ are nonintegrable, and the phase spaces of such systems are known to contain an intricate interweaving of regular and chaotic regions. Although the planets have only feeble mutual perturbations, chaotic regions must exist so that, provided a numerical integration is long enough, the solution will enter such a region. In this context, planetary chaos was in fact foreseen by Poincaré, but many today have forgotten his prediction. Nevertheless, the implications of planetary chaos are not so clear-cut as in the asteroid examples cited above. In those cases chaos determines the dynamics by forcing the asteroids close to the planets, as happened when 1989FC passed Earth in late March at only twice the moon's distance. But the planets have been around for nearly 1000 times the detected time scale for chaos in the inner planets, so in this case what does chaos mean? For Pluto, an analysis motivated by the discovery of chaos (*8*) shows that the planet's major dynamical features are unchanged despite the strength of the chaos (*9*). It is important to note that different long-term integrations of the orbits of the outer planets do generally agree, thereby implicitly validating both works. However, they also demonstrate that the role of high-order secular resonances, as well as the strength of the chaos—and possibly its very detection—depend strongly on initial conditions and the physical model used.

The curious situation today is that, as our capability to detect chaos in the motion of real objects increases, the relevance of this chaos becomes more difficult to assess.

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9. A. Milani, A. M. Nobili, M. Carpino, *Icarus*, in press.

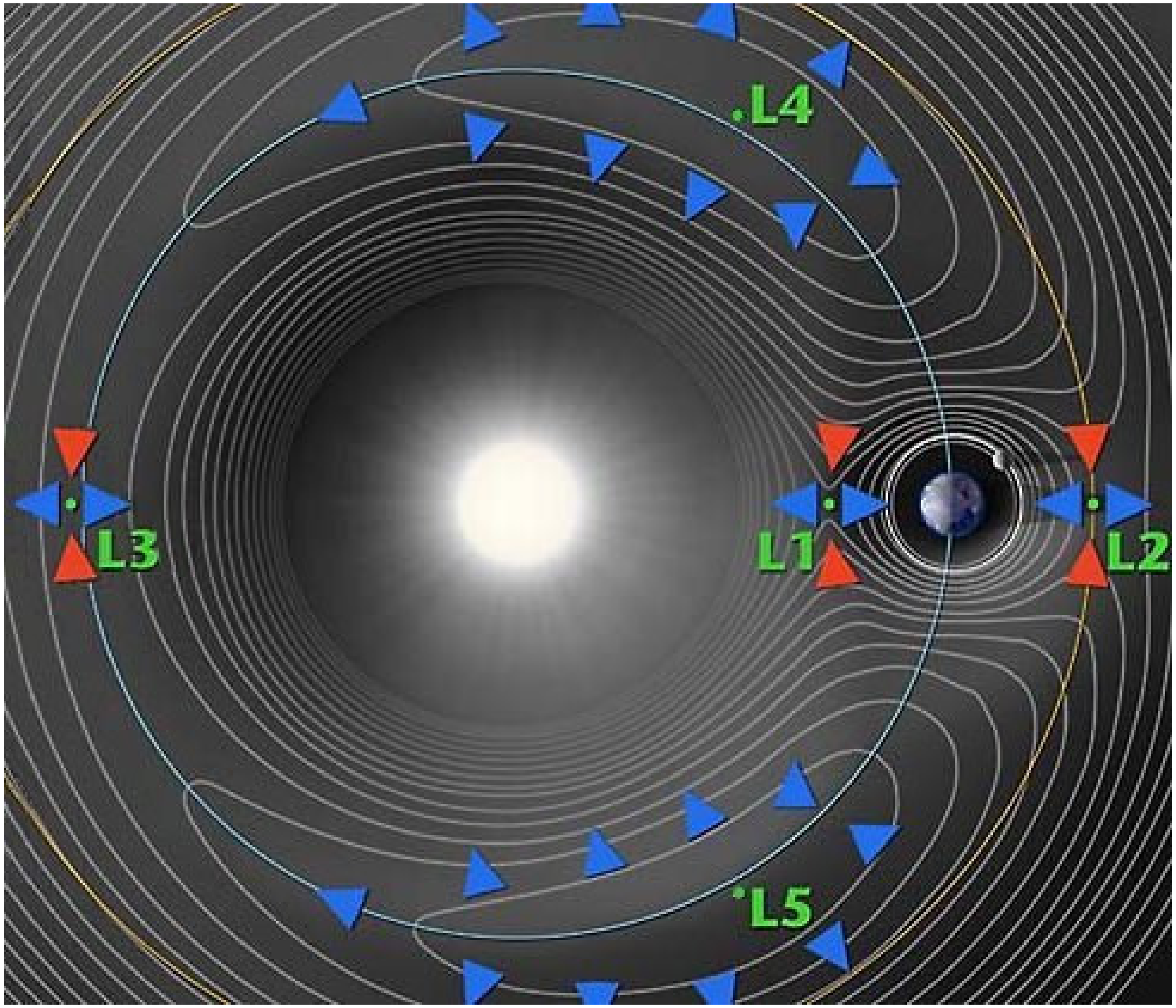
*On sabbatical leave from the University of Pisa, Pisa, Italy, with the support of the G. Colombo fellowship of the European Space Agency.

Erratum: The article "Japan faces big task in improving basic science" (News & Comment, 10 Mar., p. 1285) by Marjorie Sun stated (p. 1286) that Japan's Ministry of Education, Science, and Culture, known as Monbusho, "has only a few peer review committees." In fact, Monbusho has a few committees in each scientific specialty, such as molecular biology.

SCIENCE, Vol 244

(Nobili & Burns, Science 1989)

…by the way: is it by chance that Mercury and Venus have no Moons? (I)



Any Moon of Mercury should have been inside its Hill (or Roche) lobe

(Note: this is the rotating frame…)

$$r_{Hill} \simeq d_{\odot planet} \left(\frac{m_{\odot}}{3 m_{planet}} \right)^{1/3}$$

…by the way: is it by chance that Mercury and Venus have no Moons? (II)

Like our Moon, the satellite will slow down till its spin period equals the orbital one. At this point it can be regarded as a point mass, while the tides it generates on Mercury will determine the evolution

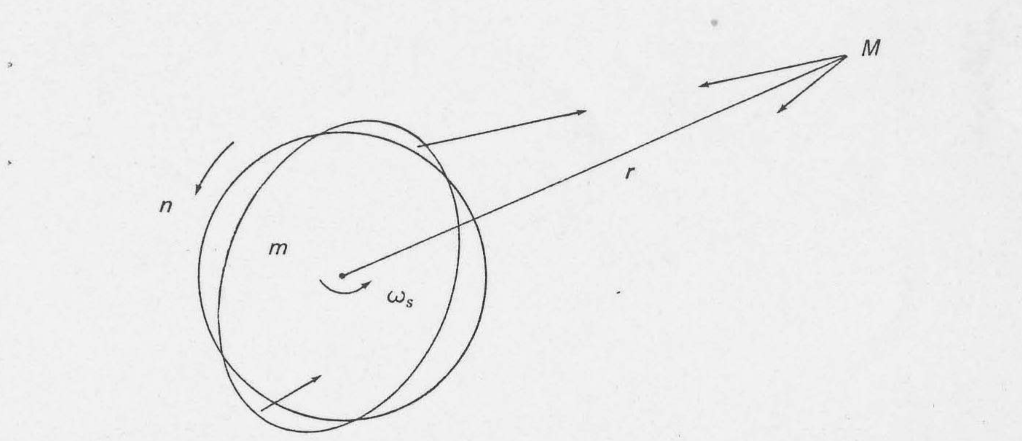


Fig. 1. M and m are the masses of planet and satellite, r is the distance between their centers, ω_s is the spin angular velocity of the satellite, n the orbital angular velocity. The plane of the sheet is the orbital plane. The figure is not on scale.

If Mercury spins faster than the satellite orbital revolution, the tidal torque will slow it down and the orbital radius increases (the satellite survives, like our Moon)

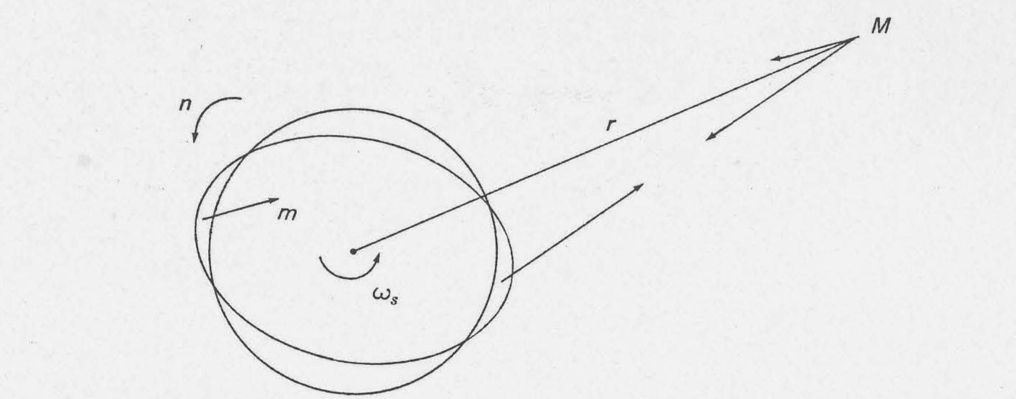


Fig. 2. M and m are the masses of planet and satellite, r is the distance between their centers, ω_s is the spin angular velocity of the satellite, n the orbital angular velocity. The plane of the sheet is the orbital plane. The figure is not on scale.

But if Mercury spins slower than the satellite orbital revolution, the tidal torque will spin it up, the satellite will come closer and closer until it is destroyed!

Which will happen for sure because of tides on Mercury from the Sun, though Mercury's initial rotation may have been fast (same for Venus..)

It is only because we are farther away form the Sun (and tidal torque goes with the 6th power of the distance) that we can have a beautiful Moon to look at!