Why do moons move away from or approach their primaries?

Detailed Response to the caught zomb from *poly*

As described at www.zombal.com

Report by *dragozzine*

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Zomb Statement:

Clarification is wanted for two aspects of the orbits of moons around planets.

1) Tidal forces are said to cause moons rotating outside the synchronous distance to recede away from the planet, while closer moons lose altitude and approach the planet. The synchronous distance is that at which a moon rotating above the equator in the direction of its rotation would appear stationary (as with Earth's geosynchronous communications satellites).

The catcher should locate and describe formulas for the rates of recession or approach, and use these formulas to calculate the current rates of recession and approach of the two small moons of Mars, Deimos and Phobos (Deimos has an orbital period of 30.3 hours, Phobos 7.6 hours [http://en.wikipedia.org/wiki/Moons_of_Mars], while Mars itself rotates in 24.63 hours). For background, the Moon has been calculated to be slowly receding from Earth at the rate of approximately 38 millimetres per year

2) What forces act to bring a moon's orbit around its primary to conform with the planet's own rotation, that is, are moons not orbiting strictly in the planet's equatorial plane moved towards conforming? Are there formulas to calculate this? As background, Saturn's main rings orbit strictly in its equatorial plane, while the outer Phoebe ring is tilted at 26.7 degrees to this plane. Phoebe and its ring also have retrograde orbits, rotating in the opposite direction to the larger moons and the rings. Do the formulas in (1) still apply for a moon in a retrograde orbit, in particular for Neptune's large moon Triton [http://en.wikipedia.org/wiki/Triton_(moon)#Orbit_and_rotation]?

Response

Abstract: Tides can change orbital dynamics when objects are close to one another. I discuss the modern theory of tides and the physical understanding that motivates them. Because tides dissipate energy and conserve angular momentum, it can be shown that they transfer angular momentum from faster spinning objects to slower spinning objects. This results in the decay of subsynchronous orbits (like Phobos) and growth of supersynchronous orbits (like Deimos), while all retrograde orbits decay. While there is significant uncertainty in how tides work in general, there is generally agreement in theories dealing with a low-mass satellite on a near-circular orbit. I present the equations used for semi-major and inclination damping. Phobos is decaying by roughly 2 cm/year, while Deimos hardly changes position over the age of the solar system. Inclination damping due to tides is effectively never important. Rings are collisional systems are are governed by a different mechanism which makes the difference between Saturn's main rings and the Phoebe ring sensible.

The vast majority of motions in the solar system can be explained by the theory of well-understood gravitational interactions alone. These interactions are entirely conservative, meaning that they do not change the overall energy of the system and, except for the sometimes chaotic interactions between planets, the motion of all bodies is entirely predictable.

On much longer timescales, bodies can come close enough to one another that different parts of the body receive different levels of gravitational attraction. The deviation from the main gravitational interaction between the bodies are called “tides” and they describe how different parts of the body are move relative to one another. Tidal forces are the forces on different parts of a body, usually given relative to the center of mass of that body, caused by the gravitational influence of another body.

Since these bodies are not perfectly rigid, the tidal forces (i.e., the differential gravitational forces) cause them to change shape ever so slightly. The change in shape creates compression or tension, i.e., the body experiencing the tidal forces is “squished”. Real objects, when squished, react in two important ways: 1) they lose energy due to friction and 2) they don't respond instantly to the tidal force, but there is a small lag in time between when the force is applied and when the body reconforms to the new equilibrium shape. Fundamentally, these are inherently linked (the more friction, the slower the time to re-equilibrate).

Let's consider a specific example, which is also the best known example of how tides between orbiting bodies work: the Earth-Moon system. There are many observations that support the effect of tides. Of course, there are high and low tides on the oceans easily visible by beach-goers; an extreme case being the Bay of Fundy. Furthermore, there are clear observations that the Earth-Moon system is losing energy (not due to interactions with any other body) in that the orbit of the Moon is increasing[1] by ~3.8 cm/year, as directly measured by lunar laser-ranging[2]. Highly detailed and complex models exist which can accurately explain the orbital deviation of the Moon and other bodies by tides. We also directly observe the tidally-induced orbital change of the Phobos, inner moon of Mars, and there are recent claims to measuring orbital changes in the Jovian and Saturnian systems as well, those these are far more subtle. There's also a lot of indirect evidence: planetary orbits that show clear signs of some kind of dissipative evolution (Miranda's inclination, Pluto-Charon double-synchronous state, even exoplanetary near-resonant systems). Those are really the only direct measurements of tides and everything else is inferred.

While the orbital dynamics are relatively well understood, how exactly real planets respond to squishing tidal forces of varying amplitudes and periods is a difficult geophysical question with minimal observational and experimental data, even for the Earth. For other bodies, our ignorance of the dissipative friction can easily be inaccurate by a factor of 10-100, with an unknown and probably complicated evolution in time. Overall, this makes calculations of the effects of tides over long timescales (e.g., millions to billions of years) very uncertain. Even where we have, by far, the most data in the Earth-Moon system, the past tidal evolution is unknown, with many competing theories.

Still, the importance of tides on orbital evolution can still be evaluated critically. Why? Because tidal effects are very strongly dependent on the separation of the bodies. Recalling that tides are the deviation from the main gravitational attraction, dimensional analysis and/or calculus give that these tidal forces decrease with distance to the third power. The back-reaction of the tides on the perturbing

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1 Orbits sometimes have the counterintuitive property that removing energy causes the orbit to expand. In reality, angular momentum is being transferred from the Earth's rotation to the Moon's orbit; when including the energy of Earth's decreased rotation, then the overall effect is net energy lost due to tidal friction, as expected. The change in the length of day of the Earth's rotation due to tides is also clearly measured.

2 The Apollo missions and some Russian lunar rovers left retroreflectors (corner cube mirrors) that allow for laser pulse to be bounced off the Moon and the time of the laser pulse to be measured extremely accurately (~cm precision per pulse).

body also falls as d^3, resulting in tides that are dependent on the sixth power of separation. What do I mean about back-reaction? To affect the Moon's orbit, the Moon raises tides on the Earth and then the Earth's tidal bulges create a gravitational torque on the Moon's orbit. (In reality, both bodies contribute, but this is the main effect.) So, increasing the distance by a factor of four reduces the already subtle effects by an additional factor of ~1000. Therefore, there is a narrow range where tides are important, beyond which they can be completely ignored even if the friction is 100 times higher than we think it is.

Wikipedia and other sources can be used to study the common tidal mechanism, which I will summarize here. I'll focus on the different mechanisms for the differing effects:

1) Despinning and change in orbital size
2) Eccentricity damping
3) Inclination and obliquity damping

<u>Despinning and semi-major axis decay</u>

Because the Earth's shape does not respond instantaneously to the Moon's position, the actual tidal bulge shape (that causes gravitational interactions) is pointing to where the Moon was ~40 minutes ago. This slight offset creates a coupling torque between the Earth and the Moon that allows for the transfer of angular momentum. While tides dissipate the total orbital+rotational energy[3], they conserve overall angular momentum. Using basic rigid body mechanics, I show below that angular momentum will always flow from the faster rotating body to the slower rotating body. Therefore, the rapidly rotating Earth (rotational period = 1 day) gives angular momentum to the Moon's orbit (revolution period = 28 days). This results in a despinning of the Earth and an increase in the orbital distance (known as the semi-major axis) between the Earth and Moon.

Proof that angular momentum flows from faster to slower objects when Energy is dissipated and angular momentum is conserved. Let L be the total angular momentum of two spinning objects. Let the objects have moments of inertia I and J and let them have angular velocities w and v. Then, the total angular momentum is L=I*w+J*v and the change in angular momentum in time is 0. Take the derivative of this equation to find dL/dt = I*(dw/dt) + J*(dv/dt), where we have assumed that the moments of inertia (which describe the distribution of mass in the spinning bodies) are fixed. The angular energy in the system is given by E = I*w*w + J*v*v. The rate of energy change in time is then dE/dt = 2*I*w*(dw/dt) + 2*J*v*(dv/dt). From dL/dt = 0, we have J*(dv/dt) = -I*(dw/dt). Substituting this in for dE/dt gives dE/dt = 2*I*w*(dw/dt) – 2*I*v*(dw/dt) = 2*I*(dw/dt)*(w-v). Since Energy is being dissipated from the system and I>0 (by definition), we have that (dw/dt)*(w-v) < 0. This means either dw/dt > 0 and w<v or dw/dt < 0 and w>v. In the first case, v is the faster angular velocity and w is spinning up; in the second case, w is the faster angular velocity and w is spinning down. Either way, angular momentum is being transferred from the faster angular velocities to slower angular velocities when energy is dissipated.

The implication for this with tides is clear. Consider the transfer of angular momentum due to the

3 Of course, overall conservation of energy is maintained. Tides are a mechanism for taking orbital and rotational energy and putting that into the increase in temperature that comes from squishing/flexing real materials. That increase is heat removes energy from the rotation + orbit. This is an irreversible process (a la the Second Law of Thermodynamics). In the case of angular momentum, one could imagine taking angular momentum from the rotation/orbit and putting it into, say, internal motion of materials. However, there's too much angular momentum to have any sensible fraction of it "dissipate" in this manner.

dissipation of energy through tides. If the spin frequency of the larger body is greater than the orbital frequency, then the larger body will slow its spin and the orbit will increase in angular momentum by growing in size[4]. If the spin frequency of the larger body is less than the orbital frequency, then the larger body will gain angular momentum and spin up while the orbit will lose angular momentum and shrink. The dividing line between these two possibilities is the orbital distance at which the spin frequency and orbital frequency are the same. This orbit is known as the synchronous orbit.

This makes sense in our understanding of lagging tidal bulges as well. For an object in sychronous orbit (for example, a communications satellite in geosynchronous orbit), there is no relative motion between the satellite and the ground. Therefore, while there can be tidal forces in this case, the tidal force relative to a single point is fixed as a function of time, so there is no "squishing" or flexure due to the movement of tidal forces. You can also show that the fully double synchronous state (where both bodies spin at the orbital frequency and the spin axes and orbit axis are aligned) is the lowest energy configuration possible; it thus makes sense that energy dissipation would eventually lead to this state. Pluto-Charon are thought to be in the double-synchronous state.

For more information on how this works, see:
http://en.wikipedia.org/wiki/Tidal_locking
which gives correct insights (though the explanations aren't spelled out in detail).

One additional note in this regard is what happens to retrograde orbits. The above argument is a simplification of the full vector formalism. In the simplified case, a retrograde orbit is like having negative angular frequency ($w<0$), in which case ($w-v$) is always negative and the orbit always decays, regardless of the position relative to the synchronous orbit.

When two orbiting objects have different masses, the despinning timescale for the smaller object is much faster. The Moon probably despun in a million years or less. Mercury is despun and Venus's slow rotation could have potentially been influenced by solar tides, though the details are complicated.

Eccentricity Damping

This is an important aspect of tidal evolution in celestial mechanics, but is not discussed in the Zomb query, so I'll cover it very briefly. There are two main effects in an eccentric orbit that cause the tidal field to vary with time, leading to flexure (squishing) that dissipates energy. First, eccentric orbits have a varying distance between the bodies. As mentioned above, the strength of tidal effects vary strongly with respect to the distance, so even a small eccentricity can lead to non-negligible tidal perturbations. Second, eccentric orbits, due to Kepler's Second Law (itself a consequence of conservation of angular momentum) have orbital motion that changes speed as a function of orbital position: the angular rate of orbital motion is faster at periapse than at apoapse. However, the body rotates at a fixed rate. This means that the position of the perturbing body moves relative to the surface as a function of the orbit. These two sets of tides, called radial and librational tides, tend to damp the eccentricity. Equations for eccentricity damping are just as uncertain as any other tidal equation. One difference is that eccentricity damping is an exponential process, e.g., the tidal rate of change of eccentricity is proportional to the eccentricity itself. So, even just a few eccentricity damping timescales can significantly reduce orbital

4 The angular momentum in an orbit is roughly $L = G*(M\_tot)*a*sqrt(1-e^2)$. Increasing the angular momentum typically means increasing a, but in can affect the eccentricity as well.

eccentricity.

In most cases in planetary science, eccentricity damping is dominated by the tides raised on the smaller body by the larger body, although tides raised on the larger body can sometimes be important and, indeed, can (according to the equations), lead to eccentricity pumping. Eccentricity evolution is also usually much faster (sometimes orders of magnitude faster) than semi-major axis decay. Many exoplanets are observed with orbits on such short orbital periods around their star (20-hour “years”) that it's a little surprising they're stable with respect to semi-major axis decay. Still, precise measurements of the eccentricities of many of these bodies show that eccentricity damping tides have worked hard and the orbits are currently very circular.

Inclination/Obliquity Damping

Inclination usually means the angle between the orbit normal vector and the spin vector of the larger body. Technically, there's nothing special about the larger body spin vector (except it usually dominates the rotational angular momentum). It can itself evolve relative to an inertial frame, so “inclination” is sometimes a moving target. In reality, the simultaneous evolution of the direction of the spin momenta vectors and the orbital angular momentum vector together need to be considered; the inclination can be derived from this. It is worth noting that there are resonances in this evolution that occur, called “Cassini States” that can additionally complicate the computations. The current inclination of the Moon's orbit around the Earth, for example, has multiple hypotheses for its origin.

When the mass ratio between the larger and smaller objects is large, the time for the rotation of the smaller body to reach the synchronous (or psuedosynchronous) rate, i.e., where the spin frequency is equal to the (average) orbital frequency (called the “mean motion”). Similarly, the time for the obliquity of the smaller object to align its spin (modulo resonant Cassini States) with the orbit is usually quite small. Ragozzine & Wolf 2009 showed, for example, that if close-in extra-solar giant planets form with some obliquity, then the obliquity of the planet has a very short damping timescale of <~1 million years (Myr). (As always, this depends on the tidal properties of the bodies involved which are not known to orders of magnitude.)

In this case of very unequal masses, you can assume that the smaller body (often called the “secondary”) has been damped to have effectively 0 obliquity and that it rotates (psuedo)synchronously. (Mercury's obliquity relative to its orbit has been damped by tidal interactions with the Sun, for example, to be <~0.01 degrees.) In this case, “inclination” has the clear meaning of the angle between the orbit normal and the spin vector of the larger body (often called the “primary”). Also note that the inclination is the same as the obliquity[5] of the primary (the angle between the primary spin axis and the orbit normal is the same as the angle between the orbit normal and the primary spin axis). In this case, one can calculate an inclination-damping timescale; it is virtually always the longest timescale in the problem (comparable or much larger than the semi-major axis evolution timescale). In the solar system, there are no clear cases where tidal damping of a satellite's inclination caused a significant change over the age of the solar system. The main exception is when the two bodies are comparable in size, in which case the full evolution of both spins and the orbit must be considered (e.g., Ragozzine & Brown 2009, Ragozzine Ph.D. Thesis, Chapter 5, Porter & Grundy

5 One must be careful with the word “obliquity”. It is the angle between the spin axis of some body relative to an orbit, but some bodies are in more than one orbit. The Earth's axis has an obliquity to the Sun (23 degrees) and an obliquity ot the Moon's orbit (~5 degrees).

2012) and it's not properly considered in the “inclination-damping” regime.

Now that we've introduced the main modes of tides, let's discuss the equations and applications to the specific questions raised in the zomb.

There are many different equations for tidal evolution. Some of the classic references are Darwin 1892, MacDonald 1960, Goldreich 1965, Kaula 1968, Hut 1981 and Mignard 1981. Most of these sources don't explain their assumptions and the implications of their equations. Very fortunately, Michael Efroimsky has recently published a series of papers that explains the assumptions, implications, and more general cases of these equations in great and useful detail. The master text with lots of detail can be found here: http://arxiv.org/abs/0803.3299; this version is continually updated even after the paper was published as Efroimsky & Williams 2009. The upshot is that most of the existing formulas have assumptions that are broken when applied to certain situations, are not derived self-consistently, and/or use models for the tidal dissipation rate as a function of frequency that are inconsistent with experimental measurements. There is also no software readily available based on their full explanations, making them difficult to test on real situations.

Even the overarching methodology espoused by all tidal theories, including Efroimsky & Williams 2009, is based on a major assumption: that tidal interactions can be represented as a superposition of large numbers of linear and decoupled forced damped harmonic oscillators (FDHOs). The only cases where this can be compared to observation are the cases where one or two of the FDHOs dominate the motion. In this case, the observations admit a free parameter, the unknown rate of tidal dissipation, so that adopting the existing methodology is likely to provide an acceptable approximation to the real answer, even if it is incorrect in actuality.

Here, we again turn to the fact that tides are a very strong function of distance, so that differences between various theories and dissipation mechanisms are often unimportant. Furthermore, the theories have similar forms in the most common (and only observed) case: a small satellite orbiting a planet in a low-eccentricity, low-inclination orbit.

Efroimsky & Lainey 2007 (http://adsabs.harvard.edu/abs/2007JGRE..11212003E) was an initial development of the full derivation of tidal equations using different assumptions. These were applied to the tidal decay of Phobos, where it was found that (in the theoretical absence of an atmosphere or tidal disruption), Phobos would hit the surface of Mars (semi-major axis decay to the radius of Mars) in 20-50 Myr, depending on the tidal model. In the grand scheme of things, the dispersion in the answers is not that different, again pointing to the fact you can use extant tidal equations in certain cases and probably get within 1-2 orders of magnitude of the correct answer.

For the case of Phobos and Deimos, we are in the regime where all the equations give very similar results (small satellites, low eccentricities and inclinations). Therefore, we choose the classic Kaula tidal equation for semi-major axis damping timescale, as given in Efroimsky & Lainey 2007:

$$\frac{da}{dt} = -\frac{3\,k_2\,R^5\,G\,m}{Q\,\sqrt{G\,(M_o + m)}\,a^{11/2}}$$

Here a is the semi-major axis, the size of the orbit, k_2 is the second-degree tidal Love number, which describes how "squishy" the primary body is, R is the radius of the primary, G is the universal gravitational constant, m is the mass of the smaller body, M_o is the mass of the primary, and Q is the famous tidal dissipation parameter. Combining these will give *da/dt* the rate of recession of the orbit of the body.

The above parameters are all well-known and classically measured, except for *k2* and *Q*. The tidal Love number is a way of parametrizing how strongly a body's gravitational field is changed when subjected to an external force (like the gravitational tidal force of a Moon). A perfectly rigid body has k2=0, while a perfectly fluid homogeneous sphere has a k2 of 1.5. You can see that, in the order of magnitude approximation, a rough estimate of 0.3 for a typical planet-sized body works well. For smaller bodies, there are formulae that can estimate k2, which can get quite small for asteroids, for example.

In the case of Mars, k2 is measured by careful satellite tracking, which yields k2=0.16. The Q is measured by actually observing the change in the orbital period associated with *da/dt*. Recalling from Kepler's Laws that the Period is directional proportional to $a^{3/2}$, measuring *dP/dt* by detecting a slow drift in the phase of Phobos in its orbit is equivalent to measuring *da/dt*. The most recent and clever measurement is to determine the position of Phobos very accurately by measuring the position of its shadow on the surface in high resolution images of Mars by Martian orbits (http://www.lpi.usra.edu/meetings/lpsc2006/pdf/2138.pdf)
For Phobos, this yields a *dP/dt* value that corresponds to a *Q* of 157 for Mars. This is comparable to the *Q* value estimated for the solid Earth of about 280. When the oceans of the Earth are included, the dissipation increases significantly giving $Q \sim 12$ for the present-day Earth. It is commonly assumed that terrestrial bodies have a constant *Q* of about 100, although this ignores significant and complex geophysical issues, as Efroimsky & Williams 2009 discuss in detail. In gas giants and stars, on the other hand, it is much more difficult to dissipate energy and *Q* values of 10^4-10^6 are commonly quoted. Lainey et al. claim to have measured the secular deceleration of Io in the Jovian system and satellites in the Saturnian system to make measurements of *Q* like those done for Mars; these give values on the dissipative side. The estimate for stars comes from the research of Zahn et al. who find that binary stars with periods less than about 10 days have circular orbits presumably due to tidal decay. Ragozzine & Wolf 2009 point out the possibility of measuring the secular deceleration due to tides with the new data from the *Kepler Space Telescope*.

While the dependence of *Q* on frequency is not known (though Efroimsky & Williams 2009 have estimates), we can for simplicity here assume that the effective *Q* for Deimos is the same as that for Phobos.

I've made a spreadsheet with all these parameters included for calculating semi-major axis decay. Keeping in mind that we're only interested in things to within an order of magnitude, the decay rate for the semi-major axis of Phobos is seen to be about 2 cm/year. The semi-major axis of Deimos is 2.5 times larger, itself reducing the decay rate by a factor of 150, but is also 6 times less massive, which reduces the decay rate by an additional factor of 6. Altogether, Deimos's orbit is changing at a rate 1000 times slower than Phobos's.

Due to the very strong dependence of *da/dt* on *a* itself, you can't do a simple extrapolation over long timescales, unless *a* doesn't change much. Deimos, however, moving by about 20 meters in 1 Myr, so even without doing this correctly, it suggests a motion over the age of the solar system that is extremely modest. (That's one of the reasons why we don't know where Phobos and Deimos came from: they look an awful lot like asteroids, but their orbits are so close to Mars and so circular that tides probably haven't changed them much. But how would asteroids get into orbits similar to the observed orbits?) The tidal decay equation, with all our assumptions, is a simple differential equation that can be solved for the semi-major axis as a function of time if you're interested in long-time extrapolations.

The assumptions that go into the above equations are not violated if you have a retrograde low eccentricity orbit like Triton's orbit around Neptune. However, the tidal Q of Neptune is not well known. A typical assumption of $Q=10^5$ gives a present-day tidal deceleration of 0.0004 m/yr. The rate is similar to Deimos, but Triton's orbit is much larger. This seems to indicate that Triton must have always had a similar orbit.

But Triton is on a crazy retrograde orbit (it's orbit is inclined 156.8 degrees relative to Neptune's spin axis! The story here (which may be related to the story for Phobos and Deimos) is that we think that Triton used to be on a highly eccentric orbit that was due to a random capture. As mentioned above, the strong dependence of tides on distance mean that all that matters is the periapse (closest approach) distance of the orbit. The current theories for Triton say that it was captured on an eccentric orbit that used to have a much lower periapse, increasing the speed of tidal evolution significantly. Eccentricity tides then damped the eccentricity to the circular orbit we see today. See http://arxiv.org/abs/1105.1179 , http://adsabs.harvard.edu/abs/2009ApJ...704L...1C , and http://adsabs.harvard.edu/abs/2005ApJ...626L.113C for the most recent explanations of Triton's orbit and tidal evolution. Note that these explanations ignore the significant complications raised by Efromisky & Williams 2009 about how to do tidal dissipation in a high eccentricity regime correctly.

Now, on to inclination damping tidal equations. The mechanism for these tides is more subtle. Recall that the tidal bulge points to where the satellite used to be due to tidal friction. On an inclined orbit, this means that the bulge can be in a slightly different plane from the orbit, creating a torque that is always acting to lower the inclination. You can imagine that this effect would be smaller than the main semi-major axis damping effect since it's only the out-of-plane component that makes a difference.

Indeed, it turns out that inclination-damping is extremely inefficient and rarely, if ever, important. An equation with all the assumptions and caveats from above, adapted from Ferraz-Mello et al. 2009 (http://arxiv.org/abs/0712.1156) is

$$\frac{dI}{dt} = -\frac{3k_2 m R^5 \sqrt{G(M_0+m)}\sin I}{2QM_0 a^{-13/2}}$$

This is also given in the attached spreadsheet. When applied to Phobos, Deimos, and Triton[6], the result

6 Note that inclination tides alone will take a retrograde orbit and move it closer to I=180 degrees, i.e., more fully retrograde.

is about 1, 10000, and 100 Gyr to move 1 degree, respectively. Phobos has one of the strongest tidal effects in the solar system, due to its very close orbit, but even it is barely affected by inclination damping tides.

While tides do move moons closer to equatorial orbits, they are so weak in this regard that many other effects can become important. Dissipation in other forms is possible, although usually bodies move through space with enormous energy and no friction. Planetary rings are different. In rings, there are many independent particles of different sizes that are all orbiting together. Imagine if one of these objects had a substantial inclination. It would eventually collide with another object (having two ring passages per half-day orbit, with the density of these rings, it's very common). The orbital velocity of the ring particles around Saturn is around 16 km/sec * sin(inclination). Thus, even a tiny inclination of 0.1 degrees would yield an impact at ~100 km/hr. Most particles are tiny (golf-ball size) puffballs of ice; an impact at this speed would completely obliterate the particle. That dissipates energy and, through conservation of momentum, reduces the inclination of whatever's left. Repeat this process uncounted trillions of times and the rings will collapse into a very very low inclination state, where there are still collisions, but they are much more gentle. This explains how Saturn's rings, despite covering hundreds of thousands of km in breadth, are only tens of meters in thickness, much thinner than a piece of paper.

However, this process requires two things: lots of particles so that collisions are common and time to allow collisions to happen. In the main rings, there are lots of particles and the rings are old (though no one is quite sure how old), so this isn't a problem. The Phoebe ring is much further away (13,000,000 kilometers from Saturn instead of the rings at 130,000 km), much more sparse (both because there is much less mass and because it is more spread out over such a large area), and is thought to be relatively young in that it is related to continual impacts on Phoebe. Therefore, these ring particles have not had time to collide and can maintain the inclination they were born with, i.e., similar to Phoebe's. None of this is effected by Phoebe's or the ring's retrograde orbit.

Note that individual ring particles are too small to exert any kind of interesting tide and are not subject to tidal decay. Even if they were, collisions and dynamical interactions with other satellites would completely dominate their inclination evolution in time.

I believe that answers the questions posed in this Zomb, along with given significant explanation. Please let me know if any of the above arguments are unclear or if you have any other questions or zombs. Doing a Google or Wikipedia search on most of the above concepts will provide helpful insights and references. Other bibliographic citations are available upon request.

Thank you for this opportunity.

Dr. Ragozzine is a Postdoctoral Researcher in the Astronomy Department at the University of Florida. He is currently funded by the United States National Aeronautics and Space Administration (NASA) to work on the NASA Kepler Space Mission. This document is his personal composition and reflects his personal opinion, not that of the University of Florida, NASA, or any other party. He has many years of research experience in the orbital dynamics of planetary systems, the Kuiper belt within our own solar system, and extra-solar planets observed around other stars.