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The Origin of Rings

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Abstract

The origin of rings is one of the final arguments in a series explaining solar system formation. Liquid moons placed in circular orbits close to the planet (inside the Roche limit) will deposit ring material as they migrate. Once outside the limit, moons retain this material. Finally, the shape of the moon, Pan, is explained, using the same mechanism that forms rings.

Keywords

Liquid, Moons, Roche Limit

1. Introduction

Planetary rings are fascinating, where their beauty only adds to the mystery of their formation. However, the mechanism of formation is one of the least understood processes related to planet formation and evolution. For a recent explanation of the formation process, see Charnoz [1]. A variety of mechanisms leading to ring formation are considered.

The origin of rings is one of the last arguments in a series explaining solar system formation (craters and tidal locking are the others). It is based on formations beginning as a liquid. As explained earlier, solar systems are believed to have a liquid phase early in development. This difficult concept is made more believable by demonstrating the origin of rings. It starts with liquid moons placed in circular orbits about the planet. Liquids far from the planet stay intact (moons)—liquids close to a planet form rings (inside the Roche limit).

The shape of the liquid (moon) is approximated as an ellipsoid and the gravity is determined on the surface at the semi-major axis. The tidal force is calculated and the distance is found where free objects are no longer held to the surface—the Roche limit. Particles free of the (liquid) surface are immediately placed in orbit, forming rings. Finally, to demonstrate the mechanism, we show how the moon, Pan, acquired its strange shape.

2. Motivation

The distance from the planet, where the tidal force becomes dominant over the self gravity of the moon, is called the Roche limit. For scientists, it seems there are only two Roche limits of interest-one for rigid moons (moons held together by chemical bonds) and one for fluid moons (moons held together by self gravity-the so called "rubble" moon).

I'm not sure what a rubble moon is, a comet, maybe? If these moons exist, they are assumed to enter the Roche limit from the outside. It would be difficult for the debris of any moon entering from the outside, to obtain the orbit we seek for rings (circular). An example of this type of moon may be the Comet Shoemaker-Levy 9. Generally, the path the particles take, is determined by the orbital character of the moons that produce them. We will dismiss the "rubble" moon for this argument in favor of the rigid moon. That is, the rigid moon holds the clue, if interpreted correctly.

Most rigid moons (the moons we actually see) are in circular orbits. If inside the Roche limit, free particles on the surface of these moons will obtain a similar orbit, with initial conditions inherited from the moon. In Figure 1(a), two objects released from opposite sides follow sleight elliptical orbits. In Figure 1(b), objects released at intervals show the pattern of rings. This is what we want. This would form rings.

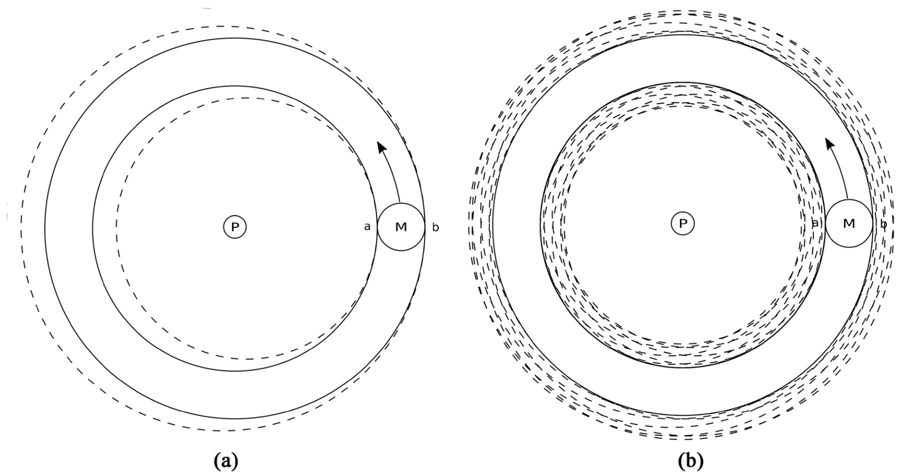

Figure 1. Ring formation of moon inside Roche limit: (a) Released particles follow elliptical paths shown as dashed lines; (b) Particles released at intervals form rings.

The problem is, rigid moons have no free particles (surface particles). If they did, the Roche limit for a rigid moon is 100,000 Km, well inside the distance to the ring's edge at 137,000 Km—for Saturn, that is. How did rings form outside this distance?

The mistake, I believe, is using a rigid moon (a solid) to calculate the Roche limit. We want to assume the moon was in a molten state (a liquid) when first placed in orbit. Then the tidal force will influence the shape (ellipsoidal) and the surface gravity of the moon (the liquid is held together by chemical bonds). The rigid moon (a sphere) is a later stage product, formed after cooling and migration.

The molten moon placed in obit must possess two properties: 1) a Roche limit that extends to the current edge of the rings (~137,000 Km) and 2) a mechanism that converts the moon to the free particles found in rings. (How the liquid moon is placed in orbit was explained earlier—The Origin of Moons.)

3. Tidal Shape of Liquids

Since the shape of the liquid will change with distance in orbit, we need to generate ellipsoids [Roche ellipsoid?] to examine the tidal behavior. Roche ellipsoids are unnecessary if we can demonstrate with a simple approximation.

For a liquid, there is little to no tensile strength. If the change in the radius is simply proportional to the forces at the surface, particularly at the axis, then the equations of the major (a) and minor (b) axis are as follows:

$$a1 = r_{moon} * \left(1 + F1/F_{moon}\right) \tag{1}$$

$$b1 = r_{moon} * \left(1 - F2/F_{moon}\right) \tag{2}$$

where

$$F_{moon} = Gm/r_{moon}^2 \tag{3}$$

$$F1 = GM/\left(d - r_{moon}\right)^2 - \left(d - r_{moon}\right)w^2 \tag{4}$$

$$F2 = \left(r_{moon}/R\right) * GM/R^2 \text{, where } R = \sqrt{d^2 + r_{moon}^2} \tag{5}$$

Then adjusting for constant volume

$$\text{ratio} = a1/b1$$

$$b = r_{moon}/\text{ratio}^{1/3}$$

$$a = b * \text{ratio}$$

Table 1. Calculated and measured dimensions for some moons of Saturn.

Saturn Moons	Calculated $a \times b\,(\times b)$ (Km)	Measured Dimensions (Km)
Titan	5152 × 5150	5149 × 5149 × 5150
Rhea	1530 × 1526	1530 × 1526 × 1525
Dione	1128 × 1120	1128 × 1123 × 1119
Tethys	1077 × 1055	1077 × 1057 × 1053
Enceladus	513 × 500	513 × 503 × 497
Mimas	416 × 387	416 × 393 × 381
Janus	209 × 166	203 × 185 × 153
Epimetheus	135 × 107	130 × 114 × 106
Pandora	103 × 72	104 × 81 × 64
Prometheus	111 × 75	136 × 79 × 59
Atlas	40 × 26	41 × 35 × 19
Pan	39 × 24	34 × 31 × 20

The only comparison for a homogeneous liquid was an approximation ($e \ll 1$) between the Earth and the moon [2], where we both calculated a tidal distortion of 50 meters—between a and b. Calculations for some moons of Saturn are listed in **Table 1** along with the measured values [3] [4].

Most moons match well. We conclude the method we use to generate ellipsoids is adequate for what we wish to demonstrate.

4. Gravitational Force of Ellipsoid

We calculate the self gravity of a liquid ellipsoidal moon at points on the surface at the semi-major axis. These are the points closest and furthest from the planet. We demonstrate with a sphere first, then move to the ellipsoid.

Usually, the gravitational force of a sphere to an external point is accomplished by summing the potential of shells – integrating them from 0 to R. But this can also be accomplished by summing the force of disks between R and $-R$.

Start with the gravitational force from a disk centered at the origin, a distance d from the point P, as shown in **Figure 2**. The integration is standard and the equations of force are Equation (6) or Equation (7):

$$2\pi Gm\sigma t\left(1-\cos\left(\alpha\right)\right) \tag{6}$$

or

$$2\pi Gm\sigma t\left[1-\frac{d}{\sqrt{R^2+d^2}}\right] \tag{7}$$

where G is the gravitational constant, m the mass at P, σ the volume density of the disk, R the disk radius, d the distance of P from the disk and t the disk thickness.

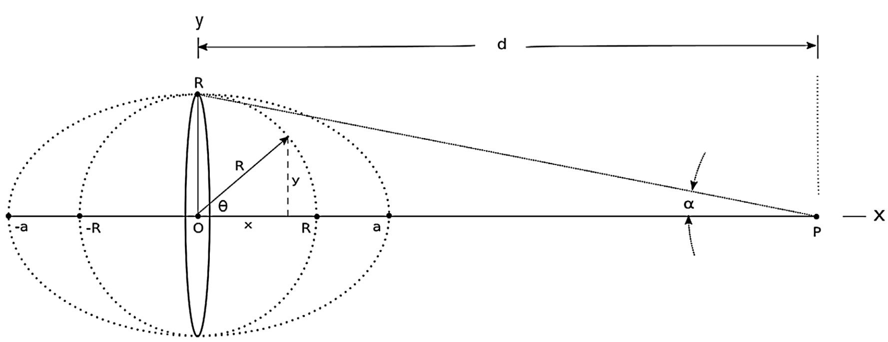

Figure 2. Gravitational force from a disk acting on a point P perpendicular to the face.

With the radius of the disk and the distance to P a function of x, we make the following substitutions in Equation (7) to get,

$$2\pi Gm\sigma\left[1-\frac{d-x}{\sqrt{\left(R^2-x^2\right)+\left(d-x\right)^2}}\right]dx \tag{8}$$

$$= 2\pi G m\sigma\left[\int_{-R}^{R}\mathrm{d}x - \int_{-R}^{R}\frac{(d-x)\mathrm{d}x}{\sqrt{(R^2-x^2)+(d-x)^2}}\right] \tag{9}$$

$$= 2\pi G m\sigma\left[2R - 2R + 2R^3/3d^2\right] \tag{10}$$

$$= GMm/d^2 \tag{11}$$

Substituting R for d, the force on the surface of the sphere can be factored as follows:

$$2\pi G m\sigma\left[\int_{-R}^{R}\mathrm{d}x - \int_{-R}^{R}\frac{(R-x)\mathrm{d}x}{\sqrt{(R^2-x^2)+(R-x)^2}}\right] \tag{12}$$

$$= 2\pi G m\sigma\left[\int_{-R}^{R}\mathrm{d}x - \int_{-R}^{R}\frac{\sqrt{R-x}\,\mathrm{d}x}{\sqrt{2R}}\right] \tag{13}$$

$$= GMm/R^2 \tag{14}$$

The equation for the ellipse is $x^2/a^2 + y^2/b^2 = 1$, $a > b$. Substituting y for R and a for d, Equation (7) for the disks becomes,

$$2\pi G m\sigma\int_{-a}^{a}\left[1 - \frac{a-x}{\sqrt{\left(b^2-\left(b^2/a^2\right)x^2\right)+(a-x)^2}}\right]\mathrm{d}x \tag{15}$$

or

$$2\pi G m\sigma\int_{-a}^{a}\left[1 - \frac{a-x)}{\sqrt{Ax^2+Bx+C}}\right]\mathrm{d}x \tag{16}$$

with

$$A = 1 - b^2/a^2, B = -2a, C = a^2 + b^2$$

The gravitational attraction on the surface of the ellipsoid at point a becomes

$$2\pi G m\sigma\left[x - (a + B/A)E + D/A\right]_{-a}^{+a} \tag{17}$$

where

$$D = \sqrt{Ax^2 + Bx + C}$$

and

$$E = \ln\left(2\sqrt{A}D + 2Ax + B\right)/\sqrt{A}$$

which can be programmed.

5. Roche Limit for Liquids

The tidal force for a homogeneous liquid ellipsoid can now be calculated. An example using the parameters for the moon Pan, the closest moon that orbits Saturn, is plotted in Figure 3. The liquid ellipsoid is represented as a solid green line using Equation (18), where a is the semi-major axis of the ellipsoid. The solid ellipsoid is represented as a solid blue line using Equation (18). The force for a rigid sphere is plotted as a dashed blue line using Equation (19), where r is the radius of the sphere.

$$F_{Tidal} = GM/(d-a)^2 - (d-a)w^2 - F_{ellipsoid}(a) \tag{18}$$

$$F_{Tidal} = GM/(d-r)^2 - (d-r)w^2 - Gm/r^2 \tag{19}$$

The plots below show the Roche limit is influenced by density and shape. The liquid ellipsoid (solid green) shows an almost exact match to the edge of the rings (~137,000 Km). This remarkable find shows the character of the moon when first placed in orbit inside the Roche limit as a liquid.

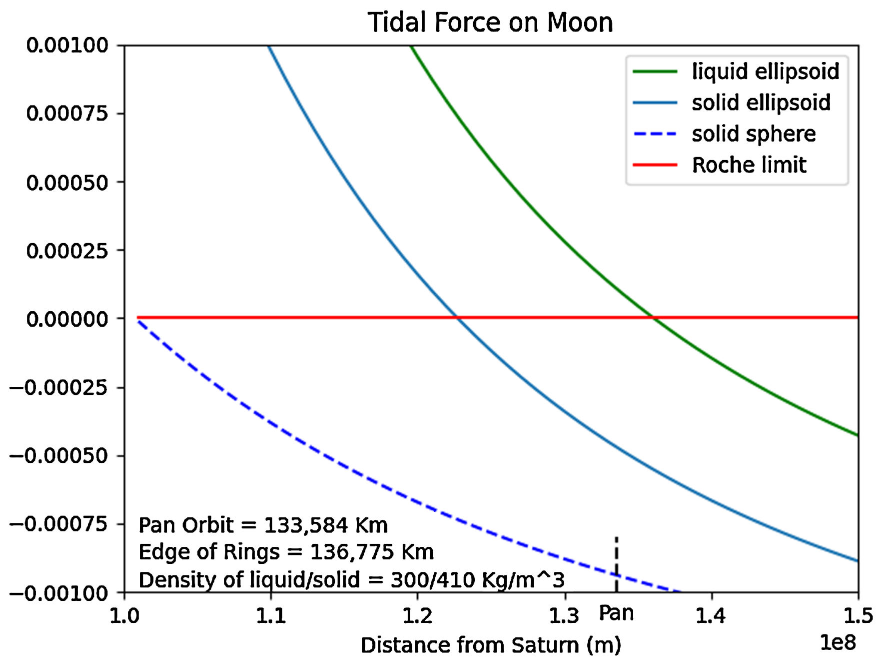

Figure 3. Tidal force for different moon types using the parameters of the moon Pan.

The solid ellipsoid (solid blue) shows a Roche limit closer to the planet (~122,000 Km). This is probably unimportant. Larger mass moons did not cool inside the Roche limit, as none have large distortions.

The Roche limit for the solid sphere is much closer to the planet. This would never cause the rings we see today. Only liquids match the ring pattern we see today.

We now need a mechanism that creates free particles.

6. Free Particles

A liquid ellipsoid and a spherically rigid moon are both held together by forces other than self gravity, *i.e.* chemical bonds. Once each cross their respective Roche limits, neither can retain objects on their surface. But neither moon has objects on the surface and as long as the moon itself is stable, nothing much should happen but a small change in shape. Mechanisms are needed creating free particles to participate in ring formation.

The tidal force would be an instinctive choice. A distorted liquid may drip (see

Tate's Law). Or crust formed from cooling may drift off the ends, if bouyant. However, both methods reduce the mass of the moon, which reduces the tidal force at the surface. Neither mechanism participates to completion. This always results in a shepard moon and shepard moons are seldom seen in rings. Further, the type of particles produced do not match the particles seen in rings.

Remembering the moon is a liquid, it becomes obvious the mechanism causing free particles has nothing to do with force, and everything to do with temperature hot liquids boil. Then rings are formed by the evaporation of a liquid moon in a circular orbit within the Roche limit. The efficiency of evaporation and the composition of the liquid determines the size of the particles placed in orbit.

We generalize the idea that all objects in orbit around a planet begin as a liquid. Larger mass moons will migrate—losing particles inside the Roche limit, retaining particles once outside. Inside the limit, smaller mass moons evaporate completely.

Near the limit, moons take an intermediate form. To demonstrate and support our argument, we explain the shape of the moon Pan (and the similar shape of Atlas).

7. The Shape of Pan

The moon Pan has a curious shape. In **Figure 4**, Pan appears flattened with a ridge, or ring, around the equator. In contrast, most moons we see are only slightly distorted from spherical. We can explain the difference if we allow moons to begin as a liquid near the Roche limit. Note: as explained earlier, lower mass moons like Pan lose the ability to migrate.

Figure 4. Pan: The innermost moon of Saturn.

Moons produce particles through evaporation (or boiling), but only lose particles near the poles along the semi-major axis (point a in our graphs). Tidal forces are greatest at the poles of the semi-major axis.

Particles are retained along the circumference of the semi-minor axis (points at b in our graphs and our future ring). Points on the semi-minor axis are the same distance as the orbital path. Tidal forces are absent along the orbital path.

Tidal forces effect the state of the matter. The lower pressure at a prolongs evaporation and the higher pressure at b promotes condensation. When a crust begins to form, it produces a ring of circumference $2\pi b$. As mass (volume) loss continues (at a), crust develops on the inside of the ring (at b). The crust is buoyant and should become self supportive (structurally) at some point. The change to the ellipsoid is diagrammed in Figure 5.

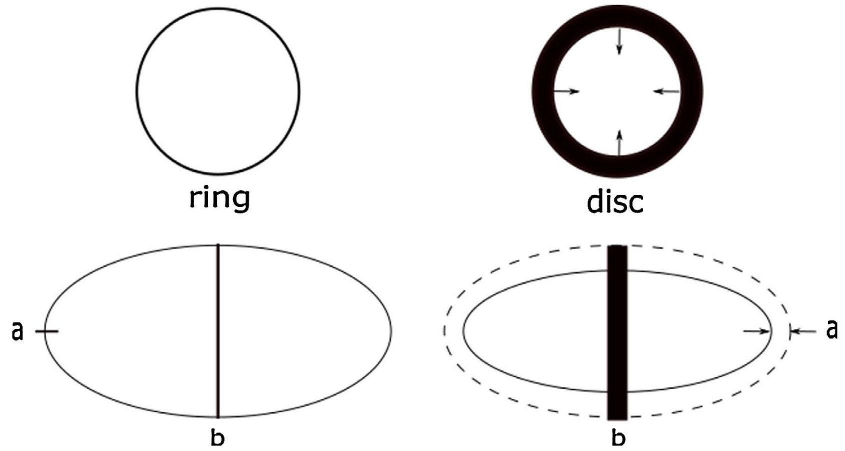

Figure 5. (Left) Ring of crust starts to form, $2\pi b$. (Right) At a later time, the ring/disc increases from the inside as the volume of ellipsoid decreases.

The next progression of changes is shown in Figure 6. The volume of the ellipsoid decreases and the size of the disk increases until a change in moment of inertia produces a 90˚ rotation about some axis in the plane of the disk. This rotation is produced by a force [moment] from the planet acting on some line in the plane of the disk, perpendicular to the axis of rotation. We chose a line through B. The result, seen in the center, is followed by a second rotation about B, aligning the disk in the plane of the orbit. This torque is represented by the arrows at the ends of the disk. Finally, the compression of the semi-major axis, still liquid, is shown on the right (and see Figure 4).

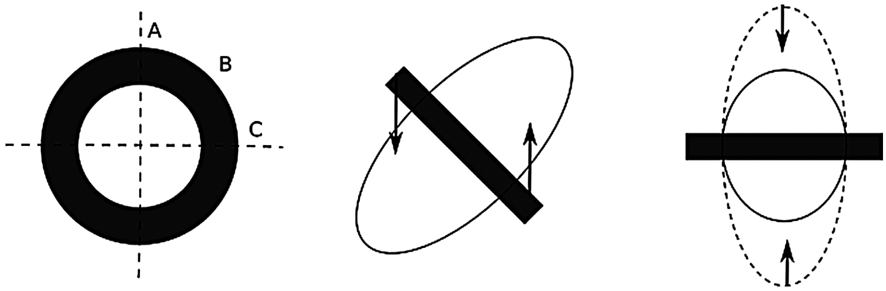

Figure 6. Left) Ellipsoid showing disk before rotation. Center) 90˚ rotation of B about center. Arrows designate torque on disk from the planet about B. Right) Disk lies in plane of orbit. Semi-major axis compresses.

8. Conclusion

We suggest liquid moons boil when placed in orbit—remaining a moon outside the limit, evaporate into a ring inside the limit and take an indeterminate shape at the limit. Pan is just inside the Roche limit, but far enough to lose mass. Slow mass loss while cooling guides the shape.

In space, liquids are a forgotten state of matter. It is hoped the arguments we present show the possibilities and encourage participation.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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