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Satellite formation from the spreading of a disk beyond the Roche limit

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Abstract

Any ring around a planet viscously spreads (like any astrophysical disk in Keplerian rotation). Beyond the Roche limit, the tidal forces from the planet are (by definition) weaker than the self-gravity of the material. Thus, a spreading ring will give birth to satellites beyond the Roche limit. The resulting bodies are then repelled by tidal interactions with the rings, and migrate outwards.

Here, we model this process in detail, and show that two regimes are possible : (i) one big Moon gathers all the material that crosses the Roche limit, (ii) a series of satellitesimals form, move away from the planet, merge, and so on, forming a chain of satellites of increasing mass and spacing with orbital radius.

We find that these two regimes apply respectively to the ring that surrounded the Earth after the Moon forming impact, and to the system of Saturn – supporting the idea that the satellites of Saturn inside Titan's orbit could be born from the spreading of initially massive rings. This goes towards a new unified model of satellite formation.

1. Introduction

It is considered since the 1970s that the Moon has formed from a disk of mostly silicated material that was ejected after a giant impact with a planetary embryo of the size of Mars [7, 1, 3]. More recently, it has been proposed that the smallest moons of Saturn (namely Atlas, Prometheus, Pandora, Epimetheus, and Janus) formed from material of the rings that spread outside of the Roche limit [5]. This process is generalized to all satellites beyond Titan by [6], after [2] suggested a model for the formation of the rings in which they were much more massive initially, accounting for the masses of all satellites until Tethys.

Thus, there seems to be a common mechanism for the formation of our Moon and the many moons of Saturn : material of a ring spreads beyond the Roche limit and spontaneously coalesces into satellite(s) ; these bodies are then repelled by the rings [8], and move away from the planet. Two regimes can be distinguished.

2. Growth of satellites from the spreading of a ring

2.1. "One Moon" regime

If all the material that flows through the Roche limit with a constant flux F ends in one single satellite, then the distance of the latter to the outer edge of the rings Δ is easily linked to the mass of the satellite. We find an expression for the mass proportional to Δ^2.

2.2. "Many moons" regime

If the newly formed satellite migrates outwards fast enough, it can't catch the fresh material expelled beyond the Roche limit, and a new satellite forms. As the migration speed decreases with Δ, the two satellites eventually approach each other and merge. In the meantime, new satellites are produced ; the new born satellites will eventually merge. Then, the mergers will also catch up and merge with each other...

With some algebra, we find the distance at which mergers occurs. We derive a simple power-law relation between the mass of the mergers and their distance to the rings, that fits satisfactorily the distribution observed in Saturn. We claim that this regime is and has been at place in Saturn's system.

2.3. Dominant regime

From considerations on the flux of material, the migration speed, and other parameters, we find, after some algebra, that the "One-Moon" regime dominates until a critical mass is reached, after which the satellites are too far from the rings and the "Many-moons" regime is entered. We find a simple and elegant expression for the critical mass, that depends only on the density of the material constituent of the rings, and the kinematic viscosity of the rings.

3. Discussion, Applications, and Conclusion

Numerical applications to the system of Saturn give a critical mass below that of the smallest moons of Saturn like Atlas, Prometheus or Pandora. Thus, the "many moon" models should prevail, which is consistent with the many moons observed.

On the other hand, the critical mass must have been that of the Moon around the Earth. After the Moon formed and couldn't accrete new material from the rings, any new formed satellites have been perturbed by the Moon and crashed into the Earth [4]. From this, we can provide constrains on the disk left after the Moon forming impact. What we find is consistent with the impact of a Mars-sized embryo. Numerical simulations will be shown.

In conclusion, is seems that the same process (the viscous spreading of a ring beyond the Roche limit) can explain the formation of satellites systems as different as that of the Earth and of Saturn.

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