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Satellites Form Fast & Late: a Population Synthesis for the Galilean Moons

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Abstract

The satellites of Jupiter are thought to have formed in a circumplanetary disc. Here we study their formation and orbital evolution with a population synthesis approach, by varying the dust-to-gas ratio, the disc dispersal timescale and the dust refilling timescale of the CPD. The initial conditions of the disc (density and temperature) are directly drawn from the results of 3D radiative hydrodynamical simulations and the disc evolution is taken into account within the population synthesis.

Our results show that the moons form fast, often within 10^4 years, and that many are lost into the planet due to fast migration, polluting Jupiter's envelope with typically 15 Earth-masses of metals. The last generation of moons can form very late in the evolution of the giant planet and the distribution of the satellite-masses is peaking slightly above Galilean masses, up until a few Earth-masses, in a regime which is observable with the current instrumentation around Jupiter-analog exoplanets orbiting sufficiently close to their host stars.

1. Introduction

Both the theories we have today on giant planet formation (Core Accretion and Gravitational Instability) predict the presence of circumplanetary discs (CPDs) made of gas and dust rotating around the forming planet in the last stage of formation [6, 7] and regular satellites (including the moons of Jupiter) are commonly thought to form in these discs.

In this work we assume a disc, that is continuously fed from the protoplanetary disc throughout its lifetime. This way, the total mass processed by the disc has been certainly enough to build several generations of Galilean-mass moons, and several of them could have been lost into the planet through migration, opening the idea of *sequential satellite-formation* [1].

2. Methods

In our work we use a population synthesis on CPD profiles that are consistent with recent radiative hydrodynamical simulations on the circum-Jovian disc. We also take into account the thermal evolution of the disc, its dispersion, and the continuous feeding of gas and dust from the vertical influx from the protoplanetary disc (e.g. [5]). Moreover, we use a dust-coagulation and evolution code to calculate the initial dust density profile corresponding to the gas hydrodynamics of the disc [2]. We assume that the initial seeds are formed from the dust via streaming instability [8].

Once the seeds are formed, their orbits are always considered circular and coplanar and orbital radii change because of the interaction between the disc and the satellites (type I migration). While these proto-satellites are migrating in the CPD, they also accrete mass from the dust disc. The gaps that form in the dust profile because of the accretion are re-filled by the material coming from the PPD, that tends to bring the dust distribution back to the one calculated by the dust-evolution code. The timescale of this refilling process, that we named *refilling timescale*, is unknown because of the large uncertainties about the dust flux from the PPD and then it used as a parameter in the population synthesis.

3. Results

Our population synthesis consisted of running 20'000 different set-ups, randomly varying 3 parameters (dust-to-gas ratio, dispersion timescale and refilling timescale). This gave us a general understanding of the properties of forming systems, depending on the parameters themselves.

3.1 Sequential formation

Due to the fact that the moonlets migrate inwards in the disc, many (even a dozen of) satellites are lost into the planet during disc evolution and therefore only the latest set of moons survive when the CPD (and PPD) dissipates. Therefore, we computed the mass, that the lost satellites bring into Jupiter: we found a distribution with a median value of $\simeq 5 \times 10^{-2} M_J \simeq 15 M_\oplus$.

If we investigate the amount of time that a system takes, starting from the beginning of the simulation, to form the last generation of surviving satellites, we find that most of the surviving satellites form between 2×10^5 and 5×10^6 years, i.e. very late in the history of Jupiter formation, when the features of the CPD have already changed a lot.

3.2 Fast formation

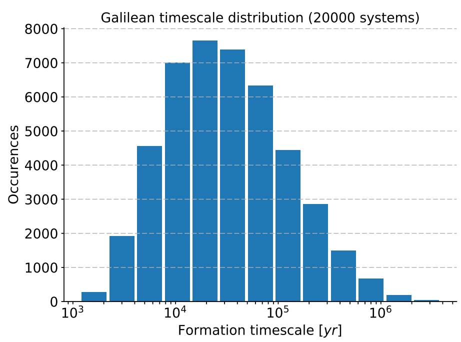

Figure 1: Histogram of the formation timescales, that distribute with a peak around 2×10^4 yr, with cases in which satellites form faster than $2 - 3 \times 10^3$ yr.

Formation timescales have an impact on the structure and composition of the moons. The three inner satellites show a layered structure, while Callisto, on the other hand, is not completely differentiated [4]. Then, while this gives a caveat about the evolution of Callisto (some believe that its formation timescale could not be shorter than $\sim 10^5$ yr) we do not have a general agreement on satellite formation timescales.

The formation timescale distribution we get from our model has a peak between 10^4 and 10^5 yr with cases also down to 10^3 yr (about 20% of the population forms less than 10^4 yr, see Figure 1). This means that satellites can even form very quickly, compared to terrestrial planet formation timescales, especially if the dust-to-gas ratio is high enough in the CPD, and the refilling mechanism is efficient.

3.3 Mass distribution

We also investigated the mass distribution of surviving satellites. According to the model, the population spreads between $10^{-7} M_J$ (i.e. the initial mass of embryos), and $10^{-2} M_J$. The peak of the distribution is between 10^{-4} and 10^{-3} M_J, which is higher than Galilean masses, often reaching Earth-mass.

4. Summary and Conclusions

In this work we investigated the formation of the Galilean satellites in a CPD around a Jupiter-like planet, using a population synthesis approach.

Due to their high masses, satellites quickly migrate into the planet via Type I migration. This means that the satellites form in sequence, and many are lost into the central planet, polluting its envelope with metals. Our results show that the moons are forming fast, often within 10^4 years (20 % of the population).

The lost satellites bring on average 15 Earth-masses into the giant planet's envelope, polluting it with metals. The high mass satellites we found in our population synthesis have intriguing implications for the future surveys of exomoons. Even with the current instrumentation, an Earth-mass moon around a Jupiter analog can be detected if the planet is orbiting relatively close to its star [3].

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