EPSC Abstracts
Vol. 13, EPSC-DPS2019-221-2, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Origin of the Galilean satellites: Slow-pebble-accretion scenario

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Abstract

It is generally accepted that the Galilean satellites formed out of the gas disk that accompanied Jupiter's formation. We construct a new scenario for the origin of the Galilean system, based on the capture of several planetesimal seeds and subsequent slow accretion of pebbles. Our "slow-pebble-accretion" scenario then simultaneously and consistently reproduces the following characteristics: (1) the mass of all the Galilean satellites; (2) the orbits of Io, Europa, and Ganymede captured in mutual 2:1 mean motion resonances; (3) the ice mass fractions of all the Galilean satellites; (4) the unique ice-rock partially differentiated Callisto and the complete differentiation of the other satellites.

1. Introduction

The physical, dynamical, compositional, and structural properties of the Galilean satellites are well known. The inner three satellites, Io, Europa, and Ganymede, are captured in mutual 2:1 mean motion resonances. The satellites' masses are similar at about 10^{-4} M_J (Jupiter mass). The satellites' ice mass fractions increase with their distance from Jupiter: Io is dry, Europa consist of 6-9% ice, while Ganymede and Callisto have ice mass fractions of about 50% [1]. Uniquely, Callisto features an undifferentiated internal structure [2].

Previous works showed that if enough satellitesimals (km-sized bodies) exist in the disk, satellites with the current Galilean satellites' mass can form by two-body collisions in the circum-Jovian disk (CJD) [3]. However, previous scenarios have only explained parts of the observed characteristics of the satellites and the models are inconsistent with each other. Also, the satellitesimal formation scenario has a problem that the progenitor dust grains will not have had the time to conglomerate, because of the strong radial drift [4].

Therefore, we construct a new alternative scenario which can reproduce these properties of the satellite system simultaneously and consistently. In our scenario, only four large planetesimals are captured by the CJD, which slowly accrete the particles (pebbles) drifting toward Jupiter. However, many parameters needed to be tuned in order to meet the constraints.

2. Results

We calculate the evolution of the mass and orbits of four planetesimal captured by the CJD one by one. Figure 1 represents the evolution of the size and orbits of the satellites. The mass (sizes) of the Galilean satellites can be reproduced very well. The dichotomy of the size between the inner and outer two satellites is created by the assumption that the pebble mass flux inside the snowline (T = 160 K) is half of that of outside because icy pebbles evaporate inside the snowline. Figure 1 also shows that all captured seeds of satellites migrate quickly (< 3×10^5 yr) by aerodynamic drag (not by Type I migration) and are captured into 2:1 resonances one by one from the inner ones. After the seeds are captured into the resonances, they grow by pebble accretion without migration and keep their orbits on the current ones. The position of Callisto is, on the other hand, different from the real orbit. It is also captured into a 2:1 resonance with Ganymede in our model.

We also find that the low ice mass fraction of Europa (6-9%) can be reproduced by the migration of the snowline at the final phase of the formation. Figure 1 shows that Europa accretes icy pebbles after 10 Myr. Europa also naturally acquired an icy surface on top of a rocky interior, because the satellite accretes dry pebbles before accreting ice-rich pebbles.

We estimate the internal temperature of Ganymede and Callisto and find that, in order to avoid the differentiation of Callisto by ^{26}Al heat, its seed must be captured by the disk late enough. Figure 2 represents the internal temperature of Ganymede (light blue) and Callisto (orange). The first one is higher than the melting point of Callisto (black) and the second one is lower than it. This means that Callisto does not melt but Ganymede may melt by ^{26}Al heat. The dichotomy of their internal ice-rock differentiation can be created by the difference in their capture time, 0.5 Myr, because the half-life of ^{26}Al is 0.717 Myr. The long growth timescale (~ 10^7 yr) is the reason why such different capture time is allowed. If the growth timescale is shorter and the difference in the capture time is the same, the final mass of Ganymede and Callisto would end up too large.

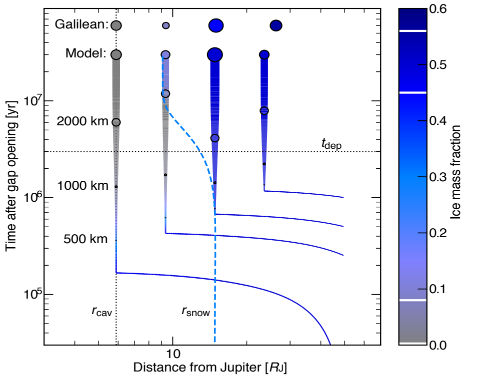

Figure 1. Evolution of the Galilean satellites. The solid curves represent the positions of the evolving satellites. The sizes of the circles represent the radii of the seeds and the current satellites. The color scales of the curves range from gray to dark blue for the increasing ice mass fractions of the seeds. The blue dashed curve represents the position of the snowline.

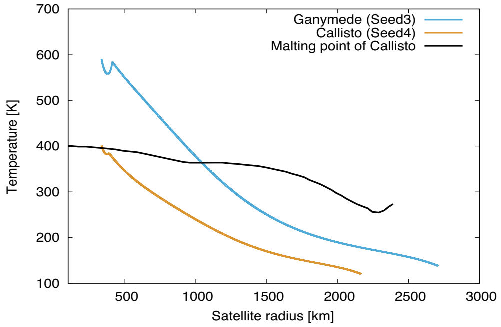

Figure 2. Internal temperature of Ganymede and Callisto. The light blue and orange curves represent the final internal temperature of Ganymede and Callisto. The black curve is the melting point of Callisto cited by Figure 5 in Barr & Canup (2008) [5]

Acknowledgements

Y.S. was supported by JSPS KAKENHI Grant Number JP16J09590. C.W.O is supported by the Netherlands Organization for Scientific Research (NWO; VIDI project 639.042.422).

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