EPSC Abstracts
Vol. 6, EPSC-DPS2011-1221, 2011
EPSC-DPS Joint Meeting 2011

Effects of Jupiter's formation and migration: the Jovian Early Bombardment

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Abstract

The first phase in the lifetime of the Solar System is that of the Solar Nebula, when the Solar System is constituted by a circumsolar disk of gas and dust particles where planetesimals and planetary embryos are forming. The giant planets should have formed during this phase, since the nebular gas represents the source material for their gaseous envelopes. Here we report the results of our investigation of the effects of Jupiter's formation on the planetesimals populating the Solar Nebula using Vesta and Ceres as case studies. Our results show that the formation of Jupiter triggered a brief yet intense phase of bombardment, which we called the Jovian Early Bombardment and whose intensity varies with the extent and the timescale of Jupiter's migration. The data that the Dawn mission will supply on Vesta and Ceres will allow us to test the Jovian Early Bombardment hypothesis and possibly gather information on the formation and the early dynamical evolution of Jupiter.

1. Introduction

The first phase in the lifetime of the Solar System is that of the Solar Nebula, when the Solar System is constituted by a circumsolar disk of gas and dust particles where planetesimals and planetary embryos are forming. The beginning of the Solar Nebula phase is conventionally assumed to coincide with the condensation of the first solids in the circumsolar disk. The end of the Solar Nebula phase is instead marked by the dispersal of the nebular gas due to the Sun entering the T Tauri phase. At the end of the Solar Nebula phase, the Solar System is composed by a protoplanetary disk populated by planetesimals, planetary embryos and the four giant planets. The giant planets should have formed in the Solar Nebula since the nebular gas represents the source material for both the massive gaseous envelopes of Jupiter and Saturn and the limited ones of Uranus and Neptune.

The formation of Jupiter is one of milestones of the history of the Solar System at the time of the Solar Nebula. According to theoretical models (see e.g. [1] and [3]), once Jupiter formed its critical core of $5 - 10$ $M_{\oplus}$, it would rapidly accrete its gaseous envelope and reach its present mass on a timescale of the order of 10^5 years. Such a fast increase in mass would changed the dynamical equilibrium in the Solar Nebula by suddenly activating the mean motion resonances with Jupiter across the orbital region now occupied by the asteroid belt. Moreover, theoretical models predict that giant planets should migrate while accreting their gaseous envelopes due to angular momentum exchange with the circumstellar disk (see e.g. [4] and references therein). Here we report the results of our first investigation of the effects of the formation of Jupiter on the planetesimals existing in the Solar Nebula using Vesta and Ceres, the two targets of the Dawn mission, as case studies.

2. The Model

We simulated the dynamical evolution of a template of the forming Solar System at the time of the formation of Jupiter's core and the subsequent accretion of its gaseous envelope. Our template of the forming Solar System was composed of the Sun, the accreting Jupiter, Vesta, Ceres and a swarm of 8×10^4 massless particles representing the disk of planetesimals and spanning between $2 - 10$ AU from the Sun. We followed the evolution of our template of the Solar System for a temporal interval equal to 2×10^6 years. We modeled the formation process of the giant planet through a semi-empirical approach: the timescales and the other parameters were derived from [1] and [3]. In our semi-empirical model we included the effects of planetary migration due to the disk-planet interactions during the formation of Jupiter (see e.g. [4] and references therein). In order to better evaluate the importance of Jupiter's migration, we considered five different scenarios: Jupiter forming at its present position, Jupiter migrating inward by 0.25, 0.5 and 1 AU with an e-folding time of 5×10^3 years and Jupiter migrating inward by 1 AU with an e-folding time of 2.5×10^4 years. During the dynamical evolution of our template of the Solar System we evaluated the probabilities of planetesimals impacting Vesta and Ceres through a statistical approach. We refer the interested readers to [5] for details on the numerical and physical model.

3. The Results

The rapid formation of Jupiter changed the dynamical equilibrium in the Solar Nebula, destabiling part of the planetesimals of the protoplanetary disks and triggering an intense bombardment in the orbital region of the asteroid belt (Jovian Early Bombardment, JEB in the following). The JEB is mainly due to two populations of planetesimals [5]: planetesimals ejected by the resonances with Jupiter (the $3:1$ and the $2:1$ resonances in the inner Solar System and the $3:2$ and $7:6$ resonances in the outer Solar System) and planetesimals formed beyond the Snow Line and scattered into the inner Solar System by Jupiter. The survival of the two target asteroids, Vesta and Ceres, to the JEB depends on the size distribution of the planetesimals populating the Solar Nebula. The abundance of large planetesimals in the disk is a critical factor for the survival of the two asteroids. If the disk of planetesimals was dominated by large bodies (i.e. $D \geq 100$ km), like in the case of planetesimals formed in turbulent circumstellar disks, the two asteroids would not have survived the JEB [5]. Conversely, disks dominated by small planetesimals (i.e. $D \leq 20$ km), like those formed in quiescent circumstellar disks or produced by collisional evolution, represent more favourable environments for the survival of Vesta and Ceres [5]. In all scenarios where they survive the JEB, Vesta and Ceres underwent an intense cratering that saturated their surfaces with craters as big as 150 km, with a tail of few bigger craters ($200 - 300$ km). Under the simplifying assumption of a uniform distribution of the craters, the JEB would have excavated a depth of about $10 - 15$ km on Vesta and of $20 - 30$ km on Ceres [5]. We refer the interested readers to [5] for further details and a more in-depth discussion of the results and their implications.

4. Discussion and Conclusions

Our results show that the formation of Jupiter triggered an intense primordial bombardment, i.e. the Jovian Early Bombardment. The intensity of the bombardment and the relative contribution of the different populations of impactors vary with the extent and the timescale of Jupiter's migration. In the most extreme scenarios, i.e. for Jupiter migrating by 0.5 AU or more and for disks dominated by large bodies (i.e. $D \geq 100$ km), the JEB could be intense enough to cause the shattering of bodies the size of Vesta or even Ceres. In all scenarios where the two asteroids survived, the JEB would strip most or all the original crust of Vesta, exposing the underlying mantle or causing large-scale effusive phenomena analogous to the lunar maria. Through the study of Vesta and Ceres, therefore, it could be possible to constrain the timescale of accretion and the dynamical evolution of the forming Jupiter and gather information on the early history of the Solar System at the time of the Solar Nebula.

Acknowledgements

This research has been supported by the Italian Space Agency (ASI) through the ASI-INAF contract I/015/07/0. The computational resources used in this research have been supplied by IFSI-INAF through the project "HPP - High Performance Planetology".

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