Icarus 209 (2010) 616–624

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Formation of Jupiter using opacities based on detailed grain physics

Naor Movshovitz [a,b,*], Peter Bodenheimer [c], Morris Podolak [b], Jack J. Lissauer [d]

[a] *Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064, USA*
[b] *Department of Geophysics and Planetary Sciences, Tel Aviv University, Ramat Aviv 69978, Israel*
[c] *UCO/Lick Observatory, Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA*
[d] *Space Science and Astrobiology Division, MS 245-3, NASA-Ames Research Center, Moffett Field, CA 94035, USA*

ARTICLE INFO

Article history:
Received 4 November 2009
Revised 24 May 2010
Accepted 3 June 2010
Available online 17 June 2010

Keywords:
Planetary formation
Jovian planets
Jupiter, Interior
Accretion

ABSTRACT

Numerical simulations, based on the core-nucleated accretion model, are presented for the formation of Jupiter at 5.2 AU in three primordial disks with three different assumed values of the surface density of solid particles. The grain opacities in the envelope of the protoplanet are computed using a detailed model that includes settling and coagulation of grains and that incorporates a recalculation of the grain size distribution at each point in time and space. We generally find lower opacities than the 2% of interstellar values used in previous calculations (Hubickyj, O., Bodenheimer, P., Lissauer, J.J. [2005]. Icarus 179, 415–431; Lissauer, J.J., Hubickyj, O., D'Angelo, G., Bodenheimer, P. [2009]. Icarus 199, 338–350). These lower opacities result in more rapid heat loss from and more rapid contraction of the protoplanetary envelope. For a given surface density of solids, the new calculations result in a substantial speedup in formation time as compared with those previous calculations. Formation times are calculated to be 1.0, 1.9, and 4.0 Myr, and solid core masses are found to be 16.8, 8.9, and 4.7 $M_\oplus$, for solid surface densities, σ, of 10, 6, and 4 g cm^{-2}, respectively. For $\sigma = 10$ and $\sigma = 6$ g cm^{-2}, respectively, these formation times are reduced by more than 50% and more than 80% compared with those in a previously published calculation with the old approximation to the opacity.

1. Introduction

The core-nucleated accretion theory of giant planet formation was effectively originated by Safronov (1972), who realized that a major part of the process involved the accumulation of solid bodies. Consider the accretion of relatively small objects (planetesimals) onto a significantly larger embryo. If $M_{\rm core}$ is the mass of the embryo, then the fundamental equation for its growth, in the absence of gas, is

$$\frac{dM_{\rm core}}{dt} = \pi R_{\rm core}^2 \sigma \Omega F_g \approx \pi R_{\rm core}^2 \sigma \Omega \left[1 + \left(\frac{v_e}{v}\right)^2\right], \quad (1)$$

where $\pi R_{\rm core}^2$ is the effective geometrical capture cross-section, σ is the surface density of solid material (planetesimals), v_e is the escape velocity from the embryo, Ω is the orbital frequency, and v is the relative velocity of embryo and planetesimal. The quantity in brackets is the gravitational enhancement factor F_g, here given in the (2 + 2)-body approximation. Safronov mentioned the later capture of gas to form giant planets, and Cameron (1973) stated that Jupiter could form by gas accretion once a solid core of about 10 $M_\oplus$ had been accreted. Perri and Cameron (1974) then constructed an adiabatic, hydrostatic equilibrium model of a protoplanet with a core and a gaseous envelope, extending outward to the Hill radius. They were able to show that there was a critical mass for the core, above which the envelope was unstable, implying that rapid gas accretion could occur. However, the value of this critical core mass was at least 70 $M_\oplus$, much higher than the deduced core masses of Jupiter and Saturn. The assumption of adiabaticity turns out to be incorrect (Stevenson, 1982), as more detailed calculations show that radiative transport with subadiabatic gradients is able to carry the energy outwards in significant portions of a growing giant planet.

Mizuno (1980) constructed models of a protoplanet including both radiative and convective energy transport in the envelope, along with an energy source provided by the planetesimals accreting onto the core at a constant rate, typically $\dot{M}_{\rm core} = 10^{-6}$ M$_\oplus$/yr. The model assumed strict hydrostatic and thermal equilibrium, and the outer radius was assumed to be the protoplanet's Hill radius. Again a critical core mass was found, above which the envelope was unstable, and the value was about 12 $M_\oplus$, close to the estimated core masses of the giant planets. Furthermore, the critical value was practically independent of the distance to the Sun, partly as a result of the assumption of the same constant value of $\dot{M}_{\rm core}$ at all distances.

The assumption of strict hydrostatic equilibrium was relaxed by Bodenheimer and Pollack (1986), who allowed quasi-static

* Corresponding author at: Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064, USA.
E-mail address: nmovshov@ucsc.edu (N. Movshovitz).

0019-1035/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2010.06.009

contraction and calculated the first evolutionary sequences applied to the core-nucleated accretion model. The planetesimal accretion rate was assumed to be constant, also at $10^{-6}\,M_{\oplus}$/yr. They found that gravitational contraction (but not dynamical collapse) began to become important at about the point where core and envelope masses were equal, at a value which later came to be known as the *crossover* mass. Rapid gas accretion also began near the crossover mass, which they found to be about 16.5 $M_{\oplus}$.

The next major step was a series of calculations by Pollack et al. (1996) who allowed a variable core accretion rate given by Eq. (1). The simulations contained three major elements: (1) three-body accretion cross-sections of solids onto the embryo (Greenzweig and Lissauer, 1992) to determine F_g, (2) a modified stellar evolution code (Henyey et al., 1964) to follow the structure and evolution of the gaseous envelope, and (3) a calculation of the trajectories of planetesimals through the gaseous envelope (Podolak et al., 1988), to deduce the deposition of solid mass and energy in the envelope and to determine the protoplanet's effective capture radius, taking into account gas drag. The often-quoted result of these calculations is that it took Jupiter 8 Myr to form in a solar nebula with $\sigma = 10$ g cm^{-2}, three times the density in the minimum mass solar nebula, under the assumption that the opacity due to small grains in the cool outer envelope was provided by grains with an interstellar size distribution and with interstellar abundances with respect to the gas. It was also shown that if the grain opacities were arbitrarily reduced to 2% of interstellar values, the formation time was reduced to about 3 Myr.

Subsequent observations of protoplanetary disks and modeling of the interior of Jupiter revealed two major problems with the Pollack et al. (1996) baseline-case results for the formation of Jupiter. First, that case gave a formation time longer than the mean lifetime of protostellar disks, and, second, it produced a core mass of about 16 $M_{\oplus}$, above the plausible range at the time of (0–11) $M_{\oplus}$, derived from matching interior models of the present Jupiter with observations (Saumon and Guillot, 2004). Further calculations (Hubickyj et al., 2005) considered, with generally improved physics, the effects of the following parameters: (1) the opacity arising from small grains in the envelope, (2) the solid surface density σ in the protoplanetary disk, and (3) a possible cutoff in core accretion rate as a result of competition for solid particles by neighboring embryos. The reduction in opacity was justified by calculations (Podolak, 2003) showing that grains entering into the protoplanetary envelope would rapidly coagulate, settle, and eventually evaporate, resulting in an actual opacity well below interstellar values. In the actual protoplanetary formation calculation the grain opacity was simply reduced to 2% of interstellar values, with the result that the formation time was reduced to under 3 Myr, half that found for interstellar values of grain opacity. The final core mass, however, still remained near 16 $M_{\oplus}$. A reduction in σ from 10 to 6 g cm^{-2}, again with the opacity at 2% of interstellar, increased the formation time to 13 Myr and reduced the core mass to 8 $M_{\oplus}$. It turned out that the constraints of short formation time and small core mass could be satisfied simultaneously only if the accretion rate of solids into the protoplanet were arbitrarily cut off at some time, simulating roughly the effect of planetesimal accretion by neighboring protoplanets. A cutoff at $M_{\rm core} = 5\,M_{\oplus}$ led to a formation time of 4.5 Myr, while a cutoff at 10 $M_{\oplus}$ gave a formation time of 1 Myr.

In the planet formation simulations of Pollack et al. (1996) and Hubickyj et al. (2005), simplified surface boundary conditions were applied during the rapid gas accretion phase. First, the gas density in the protoplanetary disk was assumed to be constant in time. Second, the gas accretion rate was capped at $10^{-2}\,M_{\oplus}$/yr, a rough estimate of the rate at which the disk could supply gas to the protoplanet as a result of its viscous evolution. Third, the outer boundary of the protoplanet was set at the modified accretion radius R_A, defined by Bodenheimer et al. (2000) to be

$$R_A = \frac{GM_p}{c_s^2/k_1 + \frac{GM_p}{(k_2 R_H)}}, \qquad (2)$$

where R_H is the Hill sphere radius, c_s is the sound speed in the disk, M_p is the planet's mass, and k_1, k_2 are constants, both set to unity. Eq. (2) is an interpolation between the Bondi accretion radius and the Hill sphere radius, such that when R_H is large, R_A reduces to the Bondi radius, and when R_H is small, R_A reduces to the Hill radius.

These assumptions were modified by Lissauer et al. (2009) to take into account the results of new 3-D numerical simulations of protoplanetary disks accreting onto protoplanets. These simulations employed the code developed by D'Angelo et al. (2003). The results from the 3-D simulations showed that $k_2 \approx 0.25$, that is, the planet can collect material from the disk only within a quarter of its Hill radius, at best. The gas accretion rates from the 3-D simulations, which included the effects of gap opening, were used whenever they were less than the accretion rate needed to maintain the boundary of the planet at R_A; thus the arbitrary cap on this rate was removed. The parameters investigated in this set of simulations included: (1) the size of the region from which the protoplanet can accrete, (2) the viscosity in the protoplanetary disk, which has a strong influence on the disk accretion rate onto the protoplanet once the envelope has shrunk and the planet is massive enough to begin clearing gas from nearby its orbit, and (3) the time-dependence of the gas density in the protoplanetary disk in the vicinity of the protoplanet. The grain opacity was set to 2% interstellar and $\sigma = 10$ g cm^{-2}. The results of these improved simulations showed that Jupiter's formation time was still less than 3 Myr, and that a relatively low-viscosity disk ($\alpha \approx 4 \times 10^{-4}$) is consistent with the formation of planets of about 1 Jovian mass, while higher viscosity produced planets that were more massive than most observed extrasolar giant planets.

In all of the simulations just mentioned, as well as in detailed formation simulations by other groups (Alibert et al., 2005; Fortier et al., 2007; Ikoma et al., 2000), the opacities arising from grains in the protostellar envelope have been approximated either by interstellar grain values (Pollack et al., 1985) or by a reduction of those values by some arbitrary amount, typically a factor 50. However, the simulations of Podolak (2003) and Movshovitz and Podolak (2008), in which grain coagulation and sedimentation were calculated for a few particular protoplanetary envelopes, showed that the ratio of actual grain opacity to interstellar grain opacity was highly variable, depending on the depth in the envelope. Near the surface of the planet the opacities were close to interstellar, while deep in the envelope they were reduced by a factor of up to 1000. Those opacity calculations, however, were not coupled to the evolution of the protoplanet, and they included only the outer radiative layer in the atmosphere, which typically has a temperature of 600 K at its inner boundary.

In the present paper we extend the basic grain settling and coagulation model of Movshovitz and Podolak (2008) by including the entire depth of the envelope down to a temperature of 1800 K, where practically all grains have evaporated. Since some layers of the outer part of the envelope are convective, we also modify the grain simulation to take into account convective effects. We then couple the grain calculation to the evolution of the protoplanet, recalculating the grain size distribution and opacity in every layer of the protoplanet at every timestep of the evolutionary calculation. These significant improvements in the core accretion model allow us to investigate the following questions: (1) How is the formation time for a Jupiter-mass planet at 5.2 AU modified compared with the earlier approximate calculations regarding the opacity?