Icarus 199 (2009) 338–350

Contents lists available at ScienceDirect

Icarus

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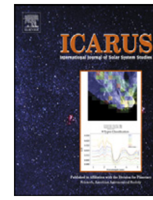

Models of Jupiter's growth incorporating thermal and hydrodynamic constraints

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ARTICLE INFO

Article history:
Received 16 August 2008
Revised 10 October 2008
Accepted 23 October 2008
Available online 12 November 2008

Keywords:
Jovian planets
Jupiter, interior
Accretion
Planetary formation
Planet–disk interaction

ABSTRACT

We model the growth of Jupiter via core nucleated accretion, applying constraints from hydrodynamical processes that result from the disk–planet interaction. We compute the planet's internal structure using a well tested planetary formation code that is based upon a Henyey-type stellar evolution code. The planet's interactions with the protoplanetary disk are calculated using 3-D hydrodynamic simulations. Previous models of Jupiter's growth have taken the radius of the planet to be approximately one Hill sphere radius, R_{H}. However, 3-D hydrodynamic simulations show that only gas within $\sim 0.25 R_{\mathrm{H}}$ remains bound to the planet, with the more distant gas eventually participating in the shear flow of the protoplanetary disk. Therefore in our new simulations, the planet's outer boundary is placed at the location where gas has the thermal energy to reach the portion of the flow not bound to the planet. We find that the smaller radius increases the time required for planetary growth by ∼5%. Thermal pressure limits the rate at which a planet less than a few dozen times as massive as Earth can accumulate gas from the protoplanetary disk, whereas hydrodynamics regulates the growth rate for more massive planets. Within a moderately viscous disk, the accretion rate peaks when the planet's mass is about equal to the mass of Saturn. In a less viscous disk hydrodynamical limits to accretion are smaller, and the accretion rate peaks at lower mass. Observations suggest that the typical lifetime of massive disks around young stellar objects is ∼3 Myr. To account for the dissipation of such disks, we perform some of our simulations of Jupiter's growth within a disk whose surface gas density decreases on this timescale. In all of the cases that we simulate, the planet's effective radiating temperature rises to well above 1000 K soon after hydrodynamic limits begin to control the rate of gas accretion and the planet's distended envelope begins to contract. According to our simulations, proto-Jupiter's distended and thermally-supported envelope was too small to capture the planet's current retinue of irregular satellites as advocated by Pollack et al. [Pollack, J.B., Burns, J.A., Tauber, M.E., 1979. Icarus 37, 587–611].

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1. Introduction

According to the core nucleated accretion model, giant planets begin their growth via the same process of agglomeration of solid bodies as do terrestrial planets; however, unlike terrestrials, the solid cores of giant planets reach masses large enough to capture substantial amounts of gas from their star's protoplanetary disk before said disk dissipates (Lissauer and Stevenson, 2007). Previous models of this process have simulated either the thermal factors that limit the ability of a planet to retain gas (Bodenheimer and Pollack, 1986; Pollack et al., 1996; Bodenheimer et al., 2000; Ikoma et al., 2000; Hubickyj et al., 2005; Alibert et al., 2005a, 2005b; Marley et al., 2007) or the disk interaction physics that governs the flow of gas to a planet (Nelson et al., 2000; D'Angelo et al., 2003; Bate et al., 2003). Here we consider both thermal and gas flow limits to giant planet growth, and present the first models of the growth of Jupiter that are constrained by detailed simulations of both of these factors.

A planet of order one to several Earth masses ($M_{\oplus}$) at a distance of about 5 AU from the central star is able to capture an atmosphere from the protoplanetary disk because the escape speed from its surface is large compared to the thermal velocity of gas in the disk. However, such an atmosphere is very tenuous and distended, with thermal pressure pushing gas outwards and thereby limiting further accretion of gas. The key factor governing the ability of a planet to accumulate additional gas when the mass of the atmosphere is less than the mass of the core is the planet's ability to radiate the energy that is provided to it by the accretion of planetesimals and gravitationally-induced compression of gas. The escape of this energy cools the gaseous envelope, allowing it to shrink and thereby enabling more gas to enter the planet's gravitational domain. Evolution occurs slowly, and hydrostatic structure is generally a very good approximation. Once a planet has enough mass for its self-gravity to compress the en-

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0019-1035/$ – see front matter Published by Elsevier Inc.
doi:10.1016/j.icarus.2008.10.004

velope substantially, its ability to accrete additional gas is limited only by the amount of gas available. Hydrodynamic limits allow quite rapid gas flow to a planet in an unperturbed disk. But a planet alters the disk by accreting material from it and by exerting gravitational torques upon it (Lin and Papaloizou, 1979; Goldreich and Tremaine, 1980). Both of these processes can lead to gap formation and isolation of the planet from the surrounding gas.

Our approach is to follow the physical structure and thermal evolution of the growing giant planet in the spherically symmetric (one-dimensional) quasi-hydrostatic approximation, and to incorporate the three-dimensional hydrodynamic interactions between the planet and the circumstellar disk via boundary conditions at the planet's outer 'surface.' Mass and energy transport within the planet are followed using the same planetary evolution code that we have employed in previous models of giant planet formation (Bodenheimer and Pollack, 1986; Pollack et al., 1996; Bodenheimer et al., 2000; Hubickyj et al., 2005; Marley et al., 2007).

Bodenheimer and Pollack (1986) prescribed the accretion rate of solids to be constant with time. Pollack et al. (1996) replaced this model by assuming that the planet was an isolated embryo that underwent runaway growth within a disk of dynamically cold, non-migrating, planetesimals. The accretion rate of solids depends upon the distribution of planetesimals as well as the planet's mass and its effective radius for accretion of planetesimals. The planet's capture cross-section was computed using the physical properties of the planet determined by the planetary structure calculation. The rate at which the planet accreted solids, $\dot{M}_Z$, for specified planet cross-section and disk surface density, eccentricities and inclinations of planetesimals within the planet's feeding zone, was determined using formulae that Greenzweig and Lissauer (1992) derived from 3-body numerical studies of planetesimal trajectories. This prescription has been used with slight modifications in most of our subsequent calculations, including all of those presented herein.

Our previous simulations have used simple *ad hoc* prescriptions for the interactions of the planet with the gaseous disk. We placed the outer boundary of the planet near its Hill sphere radius, $R_{\rm H}$, during most of its growth. The radius of the planet's Hill sphere is given by:

$$R_{\rm H} = r_p \left(\frac{M_p}{3M_\star} \right)^{1/3}, \qquad (1)$$

where M_p ($= M_{XY} + M_Z$) is the (gas + solids) mass of the planet, $M_\star$ the mass of the star, and r_p is the orbital radius of the planet. More precisely, Bodenheimer et al. (2000), Hubickyj et al. (2005), and Marley et al. (2007) took the planet's boundary to be the location where the thermal velocity of the H_2 gas molecules gave them sufficient energy to move upwards to $1R_{\rm H}$ from the planet's center. We limited the rate at which the planet could accrete gas from the disk to a maximum of $\sim 10^{-2} M_\oplus$ per year, which is approximately the Bondi rate. We extended many of our runs to a pre-determined mass limit of a Jupiter mass or more, and in a few cases we followed the ensuing phase of planetary contraction for 4.5 Gyr. But because of the approximate treatment of the later phases of gas accretion, we have always emphasized as our primary results the crossover time (when the planet's gas mass equals the mass of its condensables) and the corresponding crossover mass. The total formation time for the planet is generally only slightly longer than the crossover time.

We present herein results of new simulations using our venerable 1-D planetary formation code to follow the evolution of the planet's structure, but now incorporating 3-D hydrodynamic calculations for prescriptions of the planet's size and maximum rates of gas accretion. In some of our calculations, we gradually reduce the density of gas within the surrounding disk to provide a more realistic simulation of the final phases of the planet's growth.

In the models presented herein, we neglect orbital migration. During the phase of runaway gas accretion, the amount of radial migration that is expected before the planet reaches one Jupiter-mass is on the order of 20% of its initial orbital radius (D'Angelo and Lubow, 2008). Orbital decay due to resonant torques during the phase of slow gas accretion (Phase II) may be more substantial. However, a number of mechanisms may conspire to reduce those migration rates (see Papaloizou et al., 2007, for a review). There is presently a great deal of uncertainty surrounding these issues, so rather than rely on some poorly constrained and not yet well-understood migration mechanism, our simulations simply assume that the orbit of the planet remains fixed. The differing migration scenarios may affect giant planet growth in different ways, but our assumption of no migration is extreme in the sense that the isolation mass of a core within a planetesimal disk is larger for any non-zero migration of the planet, because the radial motion of the planet brings it into regions of the disk that are undepleted of planetesimals (Lissauer, 1993; Alibert et al., 2005a). So migrating planets, or planetesimals migrating as a result of gas drag (Kary et al., 1993; Kary and Lissauer, 1995), are likely capable of forming somewhat larger cores for a given location and disk surface mass density of solids than are the non-migrating planets that we simulate herein. Competing embryos in nearby accretion zones can act in the opposite sense from the above mentioned processes by removing solids from the planet's reach. But if the planet accretes an embryo, said embryo can bring with it solids from somewhat beyond the planet's nominal accretion zone.

Our 1-D accretion code is described in Hubickyj et al. (2005) and references therein. Details on the 3-D hydrodynamic numerical code can be found in D'Angelo et al. (2003) and references therein. We present our limits on the planet's physical extent and gas accretion rate, derived from 3-D hydrodynamic simulations, in Section 2. Section 3 discusses the physical parameters for our simulations. The results of our calculations are presented in Section 4. The scenario of capture of irregular satellites within proto-Jupiter's distended and thermally-supported envelope (Pollack et al., 1979) is discussed within the framework of our models for the growth of Jupiter in Section 5. We conclude in Section 6 with a discussion of our findings and their implications.

2. Envelope size and maximum gas accretion rates

Three-dimensional simulations of a disk with an embedded planet are used to estimate (i) the region of space within which gas is bound to a planetary core (Section 2.1) and (ii) the maximum accretion rate at which the disk can feed the inner parts of a growing planet's Hill sphere (Section 2.2).

2.1. Outer boundary of planet's envelope

In order to evaluate the volume of gas that is gravitationally bound to a planet, we adopt disk models similar to those described in D'Angelo et al. (2003). The simulation region extends from 0 to 2π in azimuth around the star and over a radial range from 2 to 13 AU, so that the disk boundaries are well separated from the planet's orbit. The pressure scale height of the disk at the planet's orbit, H_p, is taken to be 5% of the distance to the star; this corresponds to a temperature of $T = 115$ K for a gas of mean molecular weight 2.25 at a distance of 5.2 AU from a $1 M_\odot$ (solar mass) star. The dimensionless disk viscosity parameter is assumed to be $\alpha = 4 \times 10^{-3}$. We consider planet masses ranging from $10 M_\oplus$ to $50 M_\oplus$, because at smaller masses the planet's envelope is very tenuous, and because at a mass exceeding $\sim 70 M_\oplus$