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EVOLUTION OF GAS GIANT PLANETS USING THE CORE ACCRETION MODEL

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RESUMEN

Es una creencia generalizada que los planetas gigantes gaseosos se forman en un proceso de dos pasos. Un núcleo sólido crece via el acrecentamiento de planetesimales y entonces captura un envolvente masivo del gas de la nebulosa solar. Las simulaciones basadas en este modelo (Pollack et al. 1996) han tenido éxito al explicar múltiples detalles de planetas gigantes. Los modelos recientes de los interiores de Júpiter y Saturno sugieren masas de sus núcleos mucho menores a las predichas. Las nuevas simulaciones de Júpiter han sido calculadas usando diversos valores de la opacidad de granos de polvo y de la densidad superficial de los planetesimales (Hubickyj et al. 2004). Las implicaciones de detener el acrecentamiento de planetesimales sólidos a seleccionadas masas nucleares durante el crecimiento del protoplaneta, para simular la presencia de un embrion competidor, han sido exploradas. Los resultados demuestran que al decrecer la opacidad de los granos de polvo, se reduce el tiempo de evolución por más de un factor de 2. De hecho, es esta reducción de la opacidad en las porciones superiores del envolvente con temperatura T $\leq$ 500 K quien tiene el mayor efecto en la reducción del tiempo de formación. Al reducir la densidad superficial de los planetesimales, se reduce la masa final del núcleo del protoplaneta, pero se incrementa la escala de tiempo de formación. Una masa nuclear truncada, lleva a la reducción del tiempo necesario para que un protoplaneta evolucione al estadio de acrecentamiento desencadenado de gas, siempre y cuando, la masa nuclear truncada no sea muy pequeña.

ABSTRACT

Gas giant planets are generally believed to form by a two step process. A solid core grows via the accretion of planetesimals and then captures a massive envelope from the solar nebula gas. Simulations based on this model (Pollack et al. 1996) have been successful in explaining many features of giant planets. Recent interior models of Jupiter and Saturn suggest smaller core masses than had been previously predicted. New evolutionary simulations of Jupiter were computed using various values of the grain opacity and the planetesimal surface density (Hubickyj et al. 2004). The implications of halting the accretion solid planetesimals at selected core mass values during the protoplanet's growth, thus simulating the presence of a competing embryo, have been explored.

Results demonstrate that decreasing the grain opacity reduces the evolution time by more than a factor 2. In fact, it is the reduction of the grain opacity in the upper portion of the envelope with temperature T $<$ 500 K that has the largest effect on decreasing the formation time. Decreasing the surface density of the planetesimals lowers the final core mass of the protoplanet, but increases the formation timescale. A core mass cutoff results in the reduction of the time needed for a protoplanet to evolve to the stage of runaway gas accretion, provided the cutoff mass is not too small.

Key Words: **PLANETS AND SATELLITES: FORMATION — STARS: PLANETARY SYSTEMS: FORMATION**

1. FORMATION MODELS AND OBSERVATIONS

With the discovery of more than 100 extrasolar giant planets over the past decade, modeling giant planet formation has taken on an increased importance. How do gas giants form? How fast is the process? What *is* the process? The theoretical model that explains gas giant formation should explain the basic characteristics of the gas giants in our Solar System as well as those orbiting other stars. These characteristics include:

(a) Jupiter and Saturn are gas rich but still are enhanced in heavy elements compared to solar composition. Interior models of Jupiter indicate that the total solid mass ranges from 10 – 42 $M_\oplus$, of which 0 – 10 $M_\oplus$ is concentrated in the core. For Saturn, the models imply a total heavy element mass of 20 – 30

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$M_\oplus$, with a core mass between 6 – 15 $M_\oplus$ (Wuchterl et al. 2000). Uranus and Neptune models indicate heavy element masses ranging from 10 – 15 $M_\oplus$ and gaseous mass between 2 – 4 $M_\oplus$ (Pollack & Bodenheimer 1989).

(b) Observed dust disks around young stellar objects indicate ages of < 10 Myr (Cassen & Woolum 1999; Haisch et al. 2001; Lada 2003; Chen & Kamp 2004; Metchev et al. 2004). Therefore, giant planets need to form quickly.

(c) The extrasolar planets exhibit a wide range of eccentricities and semimajor axes. In a few cases there are long-period, low-eccentricity planets whose orbits are comparable to those of Jupiter and Saturn.

Presently, there are two models for the formation of the giant planets: the core accretion model, which is the subject of this paper, and the gas instability model. The core accretion model (Perri & Cameron 1974; Mizuno et al. 1978; Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996; Bodenheimer et al. 2000) forms protoplanets by the accretion of a solid core with $\sim 10\,M_\oplus$ from the planetesimals in the solar nebula; this core is then capable of capturing a massive envelope from the solar nebula gas. The gas instability model is based on the gravitational instability of the gas in the solar nebula that results in the rapid formation of a gravitationally bound subcondensation known as a giant gaseous protoplanet (Kuiper 1951; DeCampli & Cameron 1979; Boss 2000). The core accretion model has been favored for the last few decades. A general review of giant planet formation, including the core accretion model, the gas instability model, and other issues pertaining to gas giants is given by Wuchterl et al. (2000).

2. THE CORE ACCRETION MODEL

Pollack et al. (1996) provide a detailed description of core accretion models of the formation of Jupiter, Saturn, and Uranus. The *in situ* formation of extrasolar planets by core accretion was modeled by Bodenheimer et al. (2000). Several parameters were varied in these self-consistent evolutionary calculations:

(a) the planetesimal surface density,

(b) the planetesimal size,

(c) the solar nebula boundary conditions,

(d) the effect of allowing the vaporized material from the planetesimals to sink to the core or for the material to remain in the envelope where it was vaporized,

(e) the magnitude of the grain opacity, and

(f) limiting the mass of the solid core by cutting off the solid accretion at a pre-determined mass.

Briefly, we review the core accretion model (as described in Bodenheimer et al. 2000). An initial solid core is surrounded by a low-mass gas envelope that is being accreted at a much slower rate than the runaway accumulation of solid material. The solid accretion rate is greatly reduced when the solid material is depleted in the feeding zone; in contrast, the gas accretion steadily increases. All of the non-cutoff models in our core accretion simulations exhibit a phase of relatively constant accretion rate during which the gas rate is slightly greater than the solid rate of accretion. Eventually, the solid and gas masses become equal (the *crossover mass*), and shortly thereafter gas runaway occurs during which the protoplanetary mass increases rapidly. The gas accretion rate is limited to the rate at which the nebula can transport gas to the planetary vicinity. Finally, all accretion ceases and the planet contracts and cools to its present size.

The Pollack et al. (1996) models demonstrate that Jupiter and Saturn could reach the point of rapid gas accretion and form massive gaseous envelopes on timescales comparable to the lifetime of the solar nebula. The times for Uranus and Neptune to reach the point of rapid gas accretion are longer than the lifetime of the solar nebula, so these planets are unable to accrete a substantial envelope. These results demonstrate that the bulk composition characteristics of the giant planets in our Solar System come as a natural consequence of the core instability scenario. The stream of planetesimals passing through and dissolving in the envelope would explain the enhancement of metals over solar abundances in the atmospheres of the giant planets.

However, these models were computed under idealized conditions of a lone embryo orbiting around the Sun with no planetesimal migration into or out of its feeding zone. Furthermore, an acceptable formation time depends upon the assumption that the surface density of solid material in the disk was about three times as high as in the minimum mass solar nebula. In spite of these drawbacks, much progress in understanding the planetary formation process was achieved.

Pollack et al. (1996) demonstrated that the grain opacity and the planetesimal surface density in the solar nebula have substantial effects on the formation timescale of the protoplanet. The surface density (but not the opacity) affects the planet's ultimate core mass. The calculated core masses for Jupiter were generally about $20\,M_\oplus$, higher than the

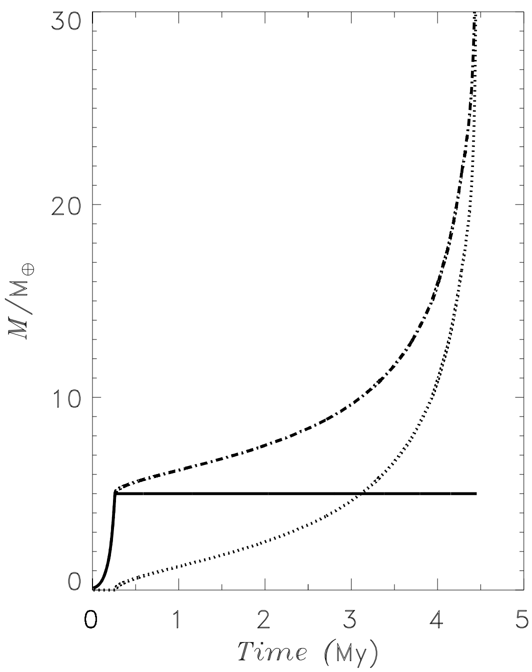

Fig. 1. Mass (units of $M_\oplus$) as a function of time (unit of million years) for the model discussed in the text. Solid line: solid mass; Dotted line: gas mass; Dash-dotted line: total mass.

deduced upper limit from the interior model calculations based on observable data (Chabrier et al. 1992; Guillot et al. 1994; Guillot et al. 1997). Calculations reported by Ikoma et al. (2000) demonstrated that a solid core of some minimum size can capture nebular gas if the grain opacity is small enough, but the smaller the core mass the longer the accretion time for the gas. This implies that a core with mass less than a minimum value, $M_{core,min}$, is unable to capture enough of the solar nebula gas *within* the lifetime of the solar nebula to make a giant gaseous planet.

3. RECENT COMPUTATIONAL RESULTS

Hubickyj et al. (2004) explore the effects of varying grain opacity, planetesimal surface density, and core cutoff mass on formation timescales in more detail. The goal of our calculations is to answer the question: Can a giant planet with a core mass of 10 $M_\oplus$ or less be produced on a time scale of a few Myr? All simulations were computed with equation of state tables based on the calculations of Saumon et al. (1995), interpolated to a near-protosolar composition of $X = 0.74$, $Y = 0.243$, $Z = 0.017$. The opacity tables are derived from the calculations of Pollack et al. (1985) and those of Alexander & Ferguson (1994). The grain opacities in these tables are

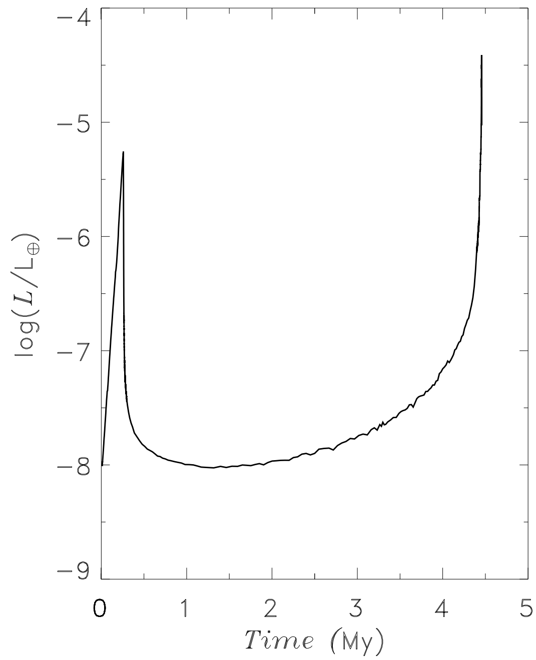

Fig. 2. Luminosity radiated by the planet as a function of time for the model discussed in the text.

based on an interstellar size distribution.

Figures 1, 2, and 3 illustrate the evolution of a protoplanet, at 5.2 AU, whose grain opacity has been reduced from the standard interstellar values by a factor 50, and in which solid accretion onto the core is stopped after it reaches 5 $M_\oplus$. The solid surface density in the initial disk is set to 10 g cm^{-2}, about three times higher than that in the minimum mass solar nebula. Figure 1 shows the mass of the core, the mass of the envelope, and the total mass as a function of time. The onset of rapid gas accretion occurs soon after the crossover mass is reached, which is about 3.0 Myr for this model, so that a Jupiter mass is expected to be accreted by 4.5 Myr, well within the time constraints provided by the disk observations. Figure 2 shows the luminosity as a function of time. It increases rapidly during the phase of core accretion (before 0.3 Myr) to a maximum of about 10^{-5} $L_\odot$. At core cutoff the luminosity drops sharply and levels off at about 10^{-8} $L_\odot$ during most of the envelope accretion phase. Once rapid gas accretion starts it increases rapidly again, reaching a peak close to $10^{-4.5}$ $L_\odot$ before gas accretion is terminated at a total planetary mass of 318 $M_\oplus$. Figure 3 shows the core radius and the total radius as a function of time. The capture radius for planetesimals is not plotted, since it is irrelevant once cutoff occurs, but other models show that the capture cross section is considerably enhanced by the presence of the gaseous

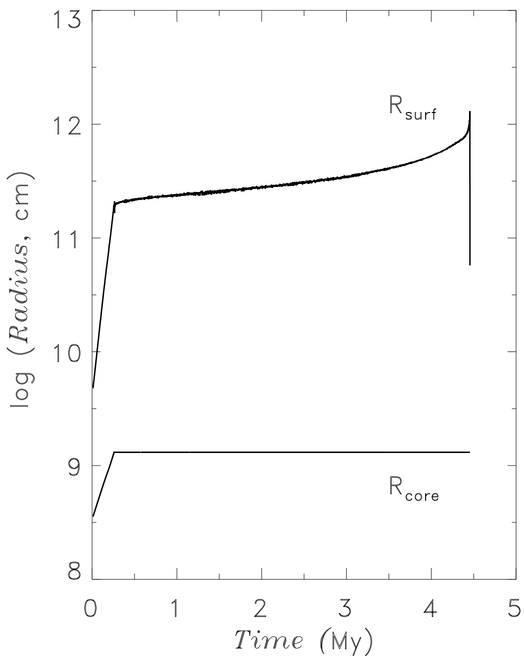

Fig. 3. The radii of the planet's core and envelope are shown as functions of time for the model discussed in the text.

envelope. By way of comparison, if the core mass is not cut off but is allowed to accrete to its normal value of $\approx 15\,\mathrm{M}_{\oplus}$, the formation time is shorter, about 2.2 Myr. If the initial solid surface density is reduced from 10 to 6 g cm^{-2}, with the core cutoff, the formation time is only slightly longer, about 4 Myr. However, if the opacity is increased to the full interstellar value, the formation time for the model with the cutoff occuring when the core mass is 5 $\mathrm{M}_{\oplus}$ becomes unreasonably long, about 90 Myr.

4. DISCUSSION AND CONCLUSIONS

Derived core masses and observed short lifetimes of protoplanetary disks strongly constrain conditions for forming gas giant planets. Early investigators of planetary formation using the core accretion model faced the problem of long formation timescales and large massive cores. The work reported in Pollack et al. (1996) and Hubickyj et al. (2004) has clearly demonstrated that these objections are not valid criticisms of the core accretion model. It appears the key to satisfying the constraints is for the grain opacity to be substantially less than the interstellar value, consistent with recent calculations of grain settling in giant planet atmospheres (Podolak 2003). The results shown here indicate that in fact a giant planet with a core mass of only 5 $\mathrm{M}_{\oplus}$, as estimated for Jupiter, can be formed on a time scale of 4 Myr, provided that core accretion is cut off before the phase of rapid gas accretion.

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