Part IV

Protoplanetary and β Pic disks

https://doi.org/10.1017/S007418090021807X Published online by Cambridge University Press

Planetary Systems in the Universe - Observation, Formation and Evolution
Proceedings IAU Symposium No. 202, ©2004 IAU
Alan Penny, Pawel Artymowicz, Anne-Marie Lagrange, & Sara Russell, eds.

Possible *in situ* Formation of Close Giant Planets in a Passive Quiescent Nebula

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Abstract. Formation of giant planets along the standard model is considered in the innermost region of protoplanetary nebulae where turbulence has already decayed. Preference of quiescent nebulae is discussed. It is shown that if dust material enough to form a core with about ten times Earth mass and the corresponding amount of gas exist in the innermost region, a giant planet with mass somewhat larger than our Jupiter can form there.

1. Introduction

The discovery of the close giant planets is a really big observational impact to the standard planetary cosmogony (e.g., Hayashi, Nakazawa, & Nakagawa 1985) which is applicable to our solar system. It appears that there exists another type of planetary systems, where the giant planets are in their orbits very close to the central stars; their orbital radii are as small as 0.05–1.0 AU. In those region ice must have evaporate and cannot exist, while ice is the main constituent of the cores of our Jovian planets in our solar system. Now we have at least two serious problems to solve: where and how were those close giant planets formed, *in situ* or somewhere? and what determined the destiny leading to formation of those close giant planets or moderate giant planets like our Jovian planets?

Recently, Bodenheimer, Hubickyj, & Lissauer (2000) presented some models of *in situ* formation of the close giant planets in turbulent nebulae. Those models are along the standard model; that is, a core first forms by accretion of planetesimals and then the core gravitationally captures surrounding nebular gas to form a massive envelope. In their models, accreting gaseous mass is supplied by radial mass flow raised by turbulent viscosity; they assume the maximum mass flow rate $[dM_{XY}/dt]_{max} = 10^{-2}M_{\oplus}/\mathrm{yr}$, where $M_{\oplus}$ is the mass of the Earth. In order to capture the gaseous mass to form the envelope, the solid core must grow by planetesimal accretion beyond the *cross-over mass* M_{cross} (or, so-called the *critical core mass*). Bodenheimer et al. found that $M_{cross} = 30 - 40M_{\oplus}$ and succeeded in *in situ* formation of the close giant planets in turbulent nebulae.

2. Why in a Passive Quiescent Nebula?

There are two reasons why quiescent nebulae seem preferable to planetary formation rather than turbulent nebulae. One is a problem of orbital decay of solid particles. Adachi, Hayashi, & Nakazawa (1976) and Weidenschilling (1977) showed that particles as large as 0.1 – 1m spiral toward the central star in gaseous nebulae in the time scale as small as $10^2 - 10^3$ years owing to insufficient drag coupling with gas and to their insufficient inertia. The particles much smaller than those sizes strongly couple with nebular gas which circulates around the central star with velocity a little smaller than Keplerian due to radial pressure gradient; hence, such small particles can avoid the rapid orbital decay above. Also the particles much larger than above sizes are hardly affected by gas drag and their motion is almost Keplerian; hence, such large particles do not have orbital decay. Dust particles grow by sticking in the nebulae and soon get the intermediate sizes above; then, they will fall toward the central star in the quite short time scale. In such situation, it seems difficult to form any planets.

However, Nakagawa, Sekiya, & Hayashi (1986) showed that in a quiescent nebula particle settling occurs and saves particles from orbital decay; that is, if dust particles are confined within a thin layer around the central plane of the nebula as a result of settling and the spatial density of the dust particles ρ_{dust} are much larger than the gas density ρ_{gas}, the motion of particles is not affected by gas to be Keplerian. Therefore, dust particles never experience orbital decay; hence, quiescent nebulae seem preferable to planetary formation, or planetary formation can start only after any turbulence decays in the nebulae.

It can be easily estimated how the nebulae should be quiescent for $\rho_{dust} >> \rho_{gas}$ or how small the well-known turbulent parameter α should be. The ratio of the half-thickness of the dust layer h to that of the gas layer H in turbulent states is estimated by the equation derived by Dubrulle, Morfill, & Sterzik (1995),

$$h/H = \sqrt{\alpha/(\Omega_K t_f)}, \tag{1}$$

where Ω_K is the Keplerian angular frequency and t_f is the frictional stopping time of dust particles. The condition $\rho_{dust} >> \rho_{gas}$ means $h/H << 1/200$ (in the ice-evaporated zone), from which we have $\alpha << \Omega_K t_f/(200)^2 < 1/(200)^2 \simeq 10^{-5}$, i.e.,

$$\alpha \lesssim 10^{-6}. \tag{2}$$

Therefore, when turbulence has decayed to the above level, the particles with any size have orbital decay no longer; then, planetary formation becomes possible.

Another reason why quiescent nebulae seem preferable is observational evidence of particle settling in protoplanetary disks. Particle settling affects the temperature distribution in the radial direction in passive quiescent disks because the photo-surfaces of the disks on which stellar radiation is absorbed descend toward the central plane according to particle settling and it causes decrease in heating efficiency with smaller angle irradiation. Change in the temperature distribution raises change in the spectral energy distribution (SED) of the disks and it provides us a probe for particle settling in the disks. Miyake & Nakagawa (1995) compared theoretical SEDs to observational ones based on the data compiled by Beckwith et al. (1990) and found that, of 16 weak lined T Tauri stars (WTTSs), 12 WTTs have a passive disk and in 6 disks of those 12 passive ones particles have settled around the central plane, and that, of 46 classical T Tauri stars (CTTs), 14 CTTs have a passive disks and in 6 disks of those 14 passive ones particles have settled. This shows that in about half of observed passive protoplanetary disks particle settling occurs; this is a large fraction.

Because of the two reasons: one is that particle settling which occurs in quiescent nebulae can save solid matter from orbital decay and another is that the observed SEDs show that particle settling really occurs in about half of passive protoplanetary disks, quiescent nebulae seem more preferable than turbulent ones for planetary formation.

3. *In situ* Formation in a Quiescent Nebula

Now we consider giant planet formation at the small radial distance $r \lesssim 1$AU in a quiescent nebula, where turbulence has already decayed to a quite low level, i.e., $\alpha \lesssim 10^{-6}$. Such a small α is required to save solid particles from orbital decay, as mentioned above. Then the radial velocity of nebular gas v_r is effectively zero; hence, there is no radial mass supply for giant planet formation. Therefore, we need high surface mass density of the nebula Σ to form a giant planet.

3.1. How high is Σ?

A solid core must grow to the *critical core mass* or *cross-over mass* M_{cross} at least in order to capture surrounding nebular gas gravitationally (Mizuno 1980); it is about $10M_\oplus$. Here we use the value of $30M_\oplus$ found by Bodenheimer et al. (2000) as M_{cross}. Since it requires the amount of solid matter as much as $30M_\oplus$, there must exists the amount of nebular gas as much as $M_{cross}/Z(\simeq 6,000M_\oplus$ or $20M_J)$ in the accretion zone, where Z is the solid mass fraction($\simeq 1/200$) and M_J is the mass of Jupiter. Such amount of mass gives a large surface density Σ $[= (M_{cross}/Z)/\pi r^2]$; e.g., about 10 times larger than in the minimum mass solar nebula model (Hayashi 1981) if the mass is distributed within 1AU, or 100 times larger if it is within 0.1AU. We should note that Σ is so high but the nebula is still gravitationally stable because Toomre's parameter $Q(= c_s\Omega_K/\pi G\Sigma$, where c_s is the sound velocity of the nebular gas and G is the gravitational constant) is about 10 in the former case and also still larger than unity in the latter case. The innermost region of the nebula is stabilized by high Ω_K as well as high c_s.

3.2. Successive Mass Accretion

Probably a solid core grows beyond the *cross-over mass* $M_{cross}(= 30M_\oplus)$ in relatively short time scale (e.g., $\lesssim 10^6$ years or so) in such inner regions. Then the nebular gas in the Hill sphere of the core begins to contract to form an envelope. The mass of the protoplanetary body M_p increases with this gas capture and so does the Hill sphere whose radius R_H is given by

$$R_H = (M_p/3M_\odot)^{1/3} r, \tag{3}$$

where the mass of the central star is assumed to be one solar mass, $1M_\odot$. The increase in R_H causes successive mass accretion onto the protoplanet.

Many numerical simulations of gas flow around proto-Jupiter have been done so far; above all, pioneer works were done by Miki (1982) and Sekiya, Miyama, & Hayashi (1987, 1988). The results of those simulations suggest that

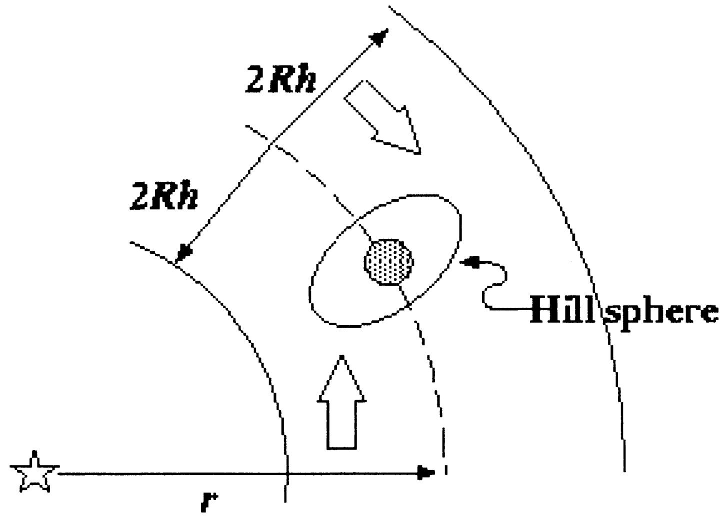

Figure 1. The nebular gas in the ring zone whose width is $2R_H + 2R_H$ around the orbit of the protoplanet can enter the Hill sphere and finally accrete onto the protoplanet.

the nebular gas in the two rings in- and out-side of the protoplanet's orbit (the width of the rings is about $2R_H$ each) can enter the Hill sphere and will finally accrete onto the protoplanet. Therefore, the protoplanet gets the gaseous mass M_{acc} which exists in the ring zone along the circle $2\pi r$ with the width $2R_H + 2R_H$(see Fig. 1), i.e.,

$$M_{acc} = (2\pi r \times 4R_H)\Sigma. \tag{4}$$

As a result, the protoplanet grows to new mass $M_p^{new}(= M_p + M_{acc})$ and has larger Hill radius R_H for M_p^{new}. Then, it will get M_{acc} for larger R_H and grow further (see Fig. 2 below).

3.3. The Final Mass

The above cycle, however, will soon stop when the mass of the protoplanet M_p reaches the final mass M_p^{final} determined by the equation $M_p = M_{acc}$, i.e.,

$$M_p^{final} = 8^{3/2}\left(\frac{M_J}{M_\odot}\right)^{1/2}\left(\frac{M_{cross}/Z}{M_J}\right)^{3/2} M_J, \tag{5}$$

$$= 0.4\left(\frac{M_{cross}/Z}{M_J}\right)^{3/2} M_J, \tag{6}$$

where the relation $\Sigma = (M_{cross}/Z)/\pi r^2$ has been used. When M_p reaches M_p^{final}, the accretion ring zone is detached from the nebula; hence, the protoplanet can

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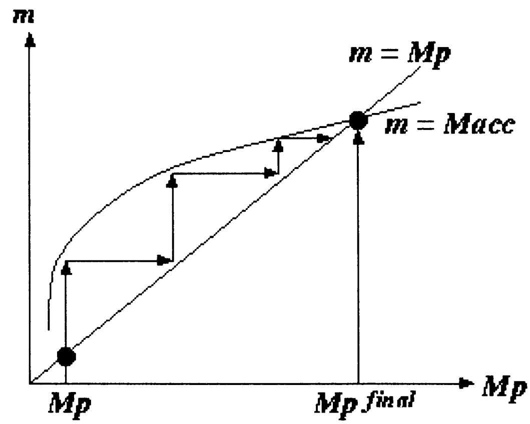

Figure 2. Note that $M_{acc} \propto M_p^{1/3}$. The accretion ring zone is detached from the nebula at $M_p = M_p^{final}$ where $M_p = M_{acc}$.

capture nebular gas no longer and does not grow any more. So the mass M_p^{final} is the final mass of the planet. Equation (6) is simple but striking; the final mass M_p^{final} is determined by M_{cross} and Z only and not dependent on the radial distance r explicitly. If we put $M_{cross} = 30M_\oplus$ and $Z = 1/200$ as the typical values in the ice-evaporated inner region, we have $M_p^{final} \simeq 10M_J$, which seems quite appropriate value compared to the masses of the observed close giant planets. In addition, if we put $M_{cross} = 10M_\oplus$ (Mizuno 1980) and $Z = 1/50$ as typical values in the ice-condensed outer region as in our Jovian planet region, we have $M_p^{final} \simeq 1M_J$; this seems to explain why our Jupiter has $1M_J$.

The solid mass fraction Z largely depends on the phase of H_2O; Z is about 1/200 in the ice-evaporated region and 1/50 in the ice-condensed region, as adopted above. Hence, the mass of the nebular gas M_{cross}/Z required to form the core with the mass M_{cross} is larger in the ice-evaporated inner region than in the ice-condensed outer region, and so is the surface mass density Σ. As a result, the giant planets born in the ice-evaporated inner region are more massive than those born in the ice-condensed region. This may be a reason why the observed close giant planets are generally more massive than our Jupiter, besides some observational bias.

4. Conclusions

We have shown that it is possible to form a giant planet in the innermost region with mass somewhat larger than our Jupiter. However, there still remain some basic problem to be solved. One is why so high surface mass density Σ is realized in the innermost region of the nebula. As mentioned above, Σ required to form a giant planet in the innermost region is about 10 – 100 times larger than in the minimum mass solar nebula. Here we can try some speculations. For example, if the turbulent eddy viscosity ν_e is a rapidly-increasing function of r and hence so is the inward radial velocity v_r, then v_r is smaller in the inner region and the nebular mass can accumulate in the inner region. As a result, after the turbulence has decayed, a mass distribution preferable to our model mentioned above will be realized. If the turbulence terminates earlier at smaller r, it will also be fine. Or, some boundary condition at the inner edge of the nebula in the viscous evolution phase may make it possible for Σ to be high in the innermost region. Another problem to be explained is what determines the destiny leading to a close-giant-planetary system or a moderate planetary system like our solar system; this is now the most important problem in the planetary cosmogony. We should explore in the regime of *comparative* planetary cosmogony.

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