Earth Planets Space, **64**, 641–648, 2012

Dust grain growth and settling in initial gaseous giant protoplanets

G. C. Paul[1], S. Datta[1], J. N. Pramanik[1], and M. M. Rahman[2]

[1]*Department of Mathematics, University of Rajshahi, Rajshahi-6205, Bangladesh*
[2]*Department of Mathematics, Shahjalal University of Science & Technology, Sylhet-3114, Bangladesh*

(Received June 20, 2011; Revised February 20, 2012; Accepted February 28, 2012; Online published August 16, 2012)

Dust grain growth and settling time inside initial gaseous giant protoplanets in the mass range 0.3 to 5 Jovian masses, formed by gravitational instability, have been investigated. We have determined the distribution of thermodynamic and physical variables inside the protoplanets solving the structure equations assuming their gas blobs to be fully convective and with this distribution we have calculated growth and settling time of grains with different initial sizes (10^{-2} cm $\leq r_0 \leq 1$ cm). The results of our calculations are found to be in good agreement with those obtained by different approaches.
Key words: Grain, convective, protoplanet, settling time, gravitational instability.

1. Introduction

The discovery of the first extrasolar planet in the mass range ~0.5 to ~3 Jupiter masses demands a reevaluation of theoretical mechanisms for giant planet formation (Boss, 1998a). The only serious alternative of the currently favored core accretion model, the disk instability model, for explaining the formation of gaseous giant planets suggests that these planets are formed as a result of gravitational fragmentation in a massive protoplanetary disk surrounding a young star (Boss, 1997; Mayer *et al.*, 2004). The basic idea of the model has been pioneered by Kuiper (1951), Urey (1966) and Cameron (1978). With the difficulties encountered with the core accretion models, this type of model, once in vogue and then quickly forgotten, has been revived and reformulated by several authors (e.g., Boss, 1997, 1998a; Boley *et al.*, 2010; Nayakshin, 2010; Cha and Nayakshin, 2011). But some investigations (e.g., Pickett *et al.*, 2000; Cai *et al.*, 2006a, b; Boley *et al.*, 2007a, b) criticized the hypothesis and generally showed that disk instabilities are unable to lead to the formation of self-gravitating dense clumps that could form gas giant protoplanets, whereas Mayer *et al.* (2002, 2004) has presented models that support the hypothesis towards the formation of long-lived giant gaseous protoplanets. According to Boss (1998b), gravitational instability proceeds very quickly, with an unstable disk breaking up into giant gaseous protoplanets, dust grains inside these protoplanets would then settle down to form a solid core within the initial contraction time which lasts about 10^5 years. In their investigation Helled *et al.* (2005) also found that during the initial contraction time grain having initial size larger than 0.01 cm can sediment to the core and if the protoplanet is convective, then even small grain can sediment to form a core. Boss (1998a, 2004) demonstrated that dust growth and sedimentation may realistically occur inside gaseous protoplanets formed by disk instability in a protoplanetary disc. Considering the grain segregation process suggested by Boss (1998a), Nayakshin (2010) estimated the process analytically as well as performed simple spherically symmetric radiation hydrodynamic simulations to test the ideas. Both analytic model and numerical simulation due to Nayakshin (2010) confirmed the suggestion made by Boss (1998a) but the initial configurations predicted by this study are found to be different from the ones found in the study of Helled and Schubert (2008). Podolak (2003) and Movshovitz and Podolak (2008) calculated the Smoluchowski equation based on more detailed physics of grains and investigated grain growth and sedimentation in the envelope of a protoplanet. Following Podolak (2003), Helled *et al.* (2008) computed thermal evaluation of a gaseous clump formed by the disk instability and examined how silicate grain growth and settling can proceed with time against convective motion, where they neglected two important effects, namely radiative heating by the surrounding medium and the contraction of the gas near the center by the increased pressure due to the core itself. The settling process was also investigated, in details, by several authors (see, e.g., McCrea and Williams, 1965; Williams and Handbury, 1974; Helled and Schubert, 2008; Paul *et al.*, 2011). All the investigations conclude that a solid core inside the protoplanets can form by sedimentation of dust grains in a reasonable short period of time. In calculating grain settling time McCrea and Williams (1965) assumed a uniform density model of a protoplanet, while Williams and Handbury (1974) investigated the problem analytically assuming a simple density distribution. But resistance of the motion of the grain and the rate of growth of the grain are functions of density. Thus the segregation time obtained by both the investigations may be somewhat different from reality. In their calculations Boss (1998b) assumed the protoplanet to be in radiative equilibrium, whereas Helled and Schubert (2008) and Helled *et al.*

doi:10.5047/eps.2012.02.006

(2008) found the gas blob to be fully convective with a thin outer radiative zone, while Paul *et al.* (2011) investigated the problem with a simple polytropic method.

In this paper we investigate dust grain growth and settling time in initial giant gaseous protoplanets, formed by disk instability, using the distribution of necessary thermodynamic variables inside the protoplanets obtained by solving their structure equations assuming the gas blobs of the protoplanets to be fully convective and intend to justify the possibility suggested by Boss (1998b) that a core of heavy elements formed in the centre of a protoplanet in a reasonably short period of time.

2. Basic Equations

2.1 Equations of protoplanetary structure

In this paper, a giant gaseous protoplanet is referred to an object in the mass range 0.3 M_J to 5 M_J (1 M_J = 1.8986×10^{30} g), the objects being formed via disk instability. Following DeCampli and Cameron (1979) and Helled *et al.* (2008), the object is assumed to be of solar composition in quasi-static equilibrium with no core in which ideal gas law holds. Helled *et al.* (2008) and Helled and Bodenheimer (2011) found initial protoplanets to be fully convective with a thin outer radiative zone. To make the work simple, we have neglected this zone and assumed such a protoplanet to be fully convective, which is consistent with Helled *et al.* (2005). Then the structure of the protoplanet can be given by the following set of equations:
The equation of hydrostatic equilibrium,

$$\frac{dP(r)}{dr} = -\frac{GM(r)}{r^2}\rho(r). \tag{1}$$

The equation of conservation of mass,

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r). \tag{2}$$

The equation of convective heat flux,

$$\frac{dT(r)}{dr} = \left(1 - \frac{1}{\gamma}\right)\frac{T(r)}{P(r)}\frac{dP(r)}{dr}. \tag{3}$$

The gas law,

$$P(r) = \frac{k}{\mu H}\rho(r)T(r). \tag{4}$$

Here all symbols have conventional meanings.

2.2 Boundary conditions

Considering a sphere of infinitesimal radius r at the centre, we find that

$$M(r) = \frac{4}{3}\pi r^3 \rho(r), \tag{5}$$

since we may treat density ρ sensibly constant in this sphere. Hence as $r \to 0$, $M(r) \to 0$. It is also clear that $M(r) = M$ at the surface, i.e., at $r = R$.

The protoplanets having cold origin must have low surface temperature. In the first approximation we assume that the surface temperature is zero. So the approximate boundary conditions can be given by

$$\left.\begin{array}{ll} T = 0,\ P = 0 & \text{at } r = R \text{ (surface)} \\ M(r) = M & \text{at } r = R \\ M(r) = 0 & \text{at } r = 0 \text{ (centre)} \end{array}\right\}. \tag{6}$$

2.3 Equation of motion

Since the protoplanets are assumed to be of solar composition, they will consist mainly of hydrogen and helium but with a proportion λ by weight of heavy elements, mostly in the form of small grains (Williams and Handbury, 1974). Since the temperature inside such a protoplanet is fairly low, the environment is quite favorable for the moving grain to coagulate between it and other grains that collide with it and grows. Following Helled *et al.* (2008), we only follow silicate grains that grow and settle as grains composed of organic material will mostly be evaporated before they get to the core region. Let a grain start moving from rest from very near to the surface towards the centre of the protoplanet under the action of the gravitational field through the ambient gas. The gas will offer resistance to the motion of the grain. Then the equation of motion of the grain at depth ζ below the surface is given by (Williams and Handbury, 1974)

$$\frac{d}{dt}\left(m_g \frac{d\zeta}{dt}\right) = \frac{GM(\zeta)m_g}{(R-\zeta)^2} - F_{\text{res}}, \tag{7}$$

whereas the appropriate equation giving the rate of growth of the grain, following Baines and Williams (1965), can be given by

$$\frac{dr_g}{dt} = \frac{\lambda\rho}{4\rho_g}\frac{d\zeta}{dt}. \tag{8}$$

In the above equations, m_g represents the mass of the grain, G the gravitational constant, R the radius of the protoplanet, $M(\zeta)$ the mass interior to a radius $R - \zeta$, F_{res} the resistive force, r_g the radius of the grain and ρ_g represents the density of the grain materials.

Now the expression for the resistance to the motion of the grain is given either by Epstein drag or Stocks' drag depending on whether the mean path of the particles is greater or less than the radius of the grain. With the obtained density distribution shown in Fig. 3 and with the assumed initial radii of the grains, the mean free path can be found to be smaller than their initial radii. Also the falling grains are growing, so the relevant resistance law to the motion of the falling grains is given by due to Stokes' being given by

$$F_{\text{res}} = 6\pi\eta r_g \frac{d\zeta}{dt}, \tag{9}$$

where η is the coefficient of viscosity. It is noted that Paul *et al.* (2011) investigated grain growth and grain sedimentation time inside a giant gaseous protoplanet of mass $M = 2 \times 10^{30}$ g and radius $R = 3 \times 10^{12}$ cm assuming the gas blob of the protoplanet to be polytropic taking into account the same set of equations presented in this section.

3. Solution

3.1 Protoplanetary structure

As is usual in numerical work, the governing equations as well as the boundary conditions were non-dimensionalized with the help of the following transformations: $r = (1 - y)R$, $M(r) = q(y)M$, $T(r) = \frac{\mu HGM}{kR}\theta(y)$, $P(r) = \frac{GM^2}{4\pi R^4}p(y)$.

Using the above transformations and with the help of Eq. (4), Eqs. (1)–(3) as well as the boundary conditions

Table 1. Grain sedimentation time.

M/M_J	R (cm)	Time in year ($r_0 = 1$ cm)	Time in year ($r_0 = 10^{-1}$ cm)	Time in year ($r_0 = 10^{-2}$ cm)
0.3	3.5×10^{12}	9.87×10^{1}	2.17×10^{3}	3.58×10^{4}
1.0	5.3×10^{12}	1.37×10^{2}	2.92×10^{3}	4.57×10^{4}
3.0	7.8×10^{12}	1.91×10^{2}	3.91×10^{3}	5.85×10^{4}
5.0	8.4×10^{12}	1.52×10^{2}	2.97×10^{3}	4.23×10^{4}

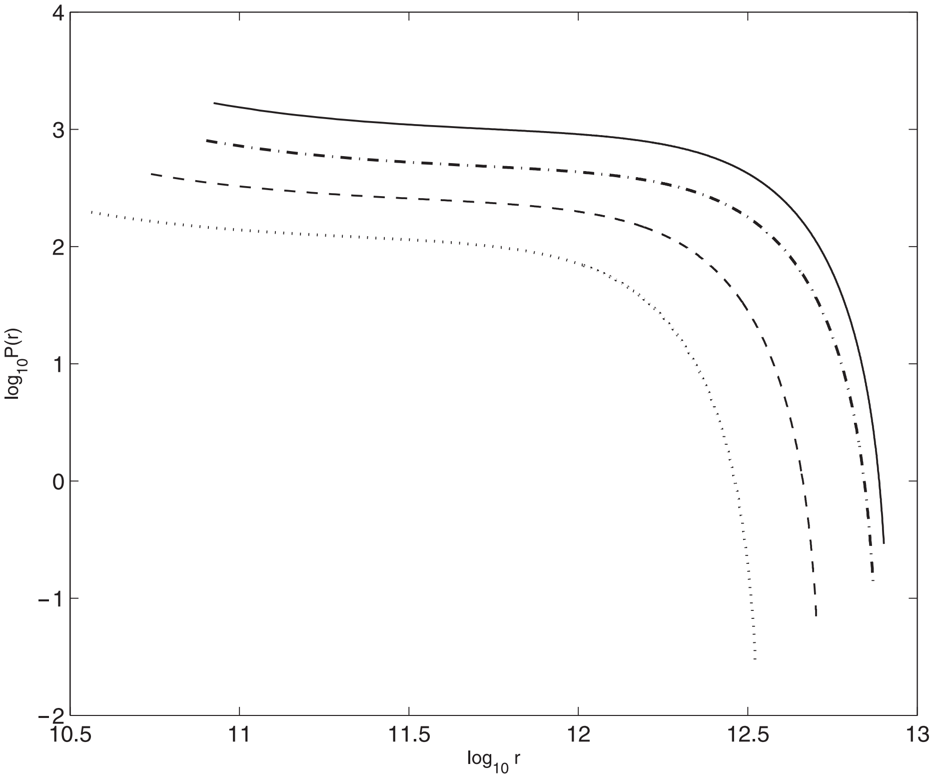

Fig. 1. Pressure profiles inside some protoplanets. The dotted, dashed, dashed-dotted and solid curves show the initial configuration for objects with 0.3, 1, 3 and 5 Jupiter masses respectively.

given by Eq. (6) can be written respectively as

$$\frac{dp}{dy} = \frac{pq}{\theta(1-y)^2}, \tag{10}$$

$$\frac{dq}{dy} = -\frac{p(1-y)^2}{\theta}, \tag{11}$$

$$\frac{d\theta}{dy} = \left(1 - \frac{1}{\gamma}\right)\frac{q}{(1-y)^2}, \tag{12}$$

$$\left.\begin{array}{lll} \theta = 0, \ p = 0 & \text{at } y = 0 \text{ (surface)} \\ q = 1 & \text{at } y = 0 \\ q = 0 & \text{at } y = 1 \text{ (centre)} \end{array}\right\}. \tag{13}$$

For solving Eqs. (10)–(12), because of the existence of the singularity, approximate surface boundary conditions have been developed near the boundary by the method of series solution and are given by

$$\theta = \frac{2y}{5(1-y)} p = e\theta^{\frac{5}{2}}, \quad \text{and} \quad q \approx 1 \text{ at } y \approx 0,$$

where e is an arbitrary constant.

In our calculation, the used values of masses and radii are taken from the study of Helled and Schubert (2008) and are presented in Table 1. Also, we have used $\gamma = 5/3$, as is appropriate for a monoatomic gas. Following Paul *et al.* (2008), we have used $e = 45.4$ for which the third condition given by Eq. (13) is satisfied. Furthermore, we have used $\mu = 2.3$ (Boley *et al.*, 2010), as is appropriate for molecular hydrogen, and all other parameters involved in the problem have been assumed to have their standard values. Inserting all the values of the parameters involved, we have solved Eqs. (10)–(12) by the fourth order Runge-Kutta method from $y = 0.01$ to $y = 0.99$. The results of our calculation are presented in diagrammatic form in Figs. 1–3.

3.2 Growth of grains and solution of the equation of motion

It is obvious that Eq. (7) cannot be solved analytically. In general, any body moving in a resisting medium reaches a velocity close to its terminal velocity very quickly and then proceeds to travel at such a velocity. If we assume this case for the falling grain, we can neglect the acceleration term. With this simplification, Eq. (7) can be written as

$$\frac{d\zeta}{dt}\frac{dm_\mathrm{g}}{dt} = \frac{GM(\zeta)m_\mathrm{g}}{(R-\zeta)^2} - 6\pi\eta r_\mathrm{g}\frac{d\zeta}{dt}. \tag{14}$$

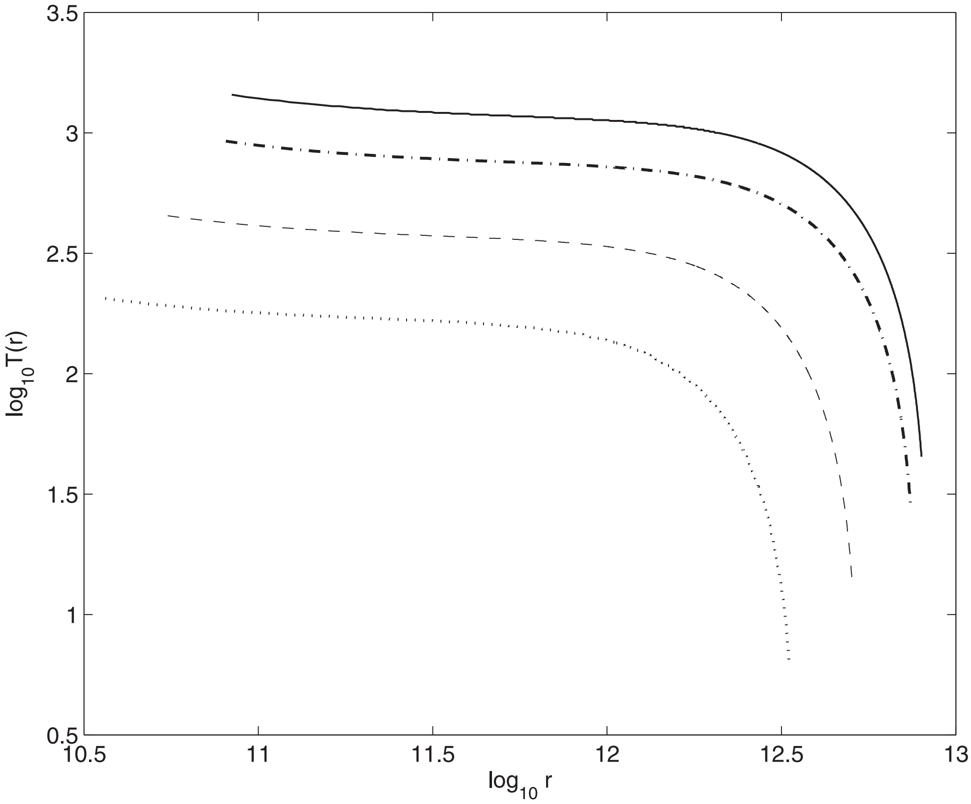

Fig. 2. Temperature profiles inside some protoplanets. The dotted, dashed, dashed-dotted and solid curves show the initial configuration for objects with 0.3, 1, 3 and 5 Jupiter masses respectively.

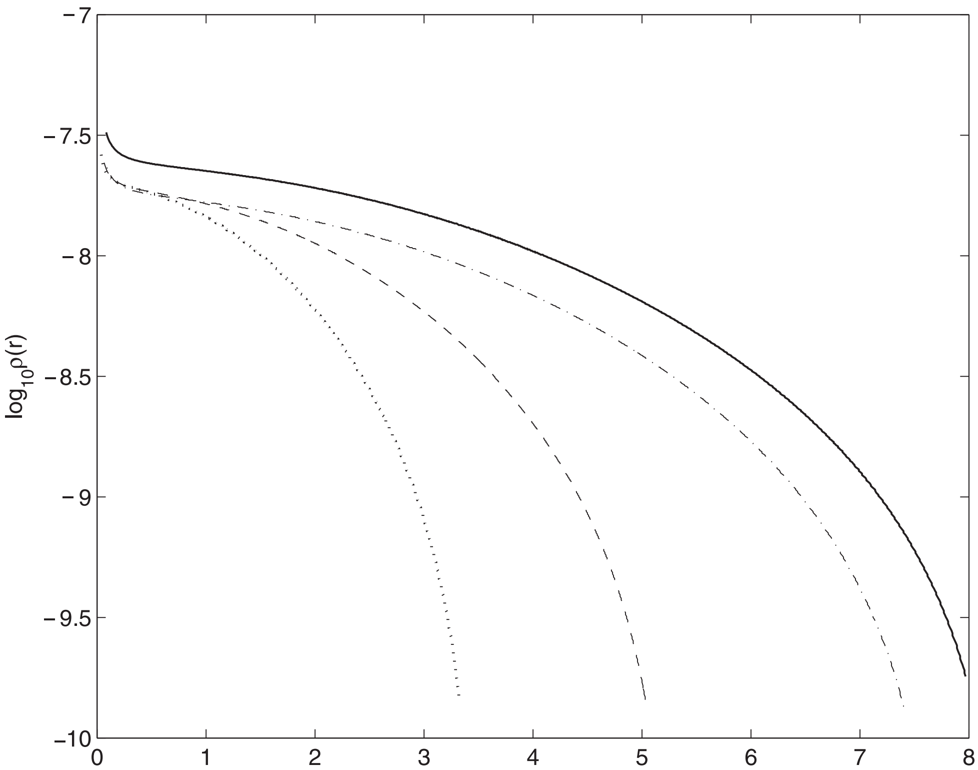

Fig. 3. Density distribution inside some protoplanets. The dotted, dashed, dashed-dotted and solid curves show the initial configuration for objects with 0.3, 1, 3 and 5 Jupiter masses respectively.

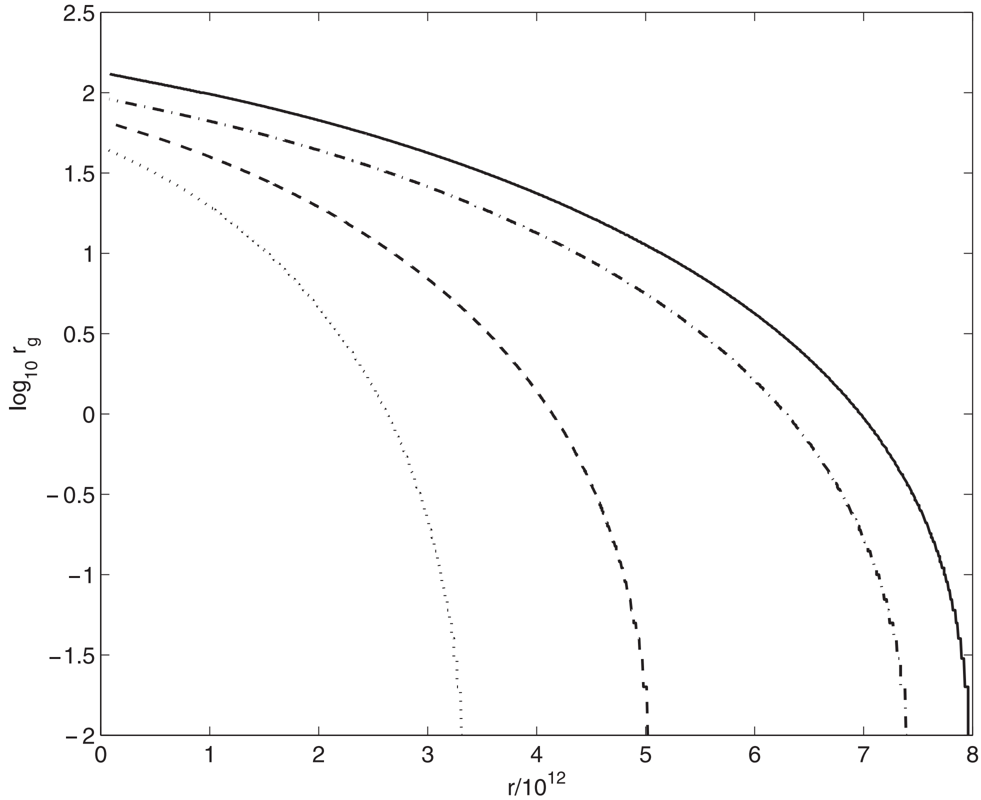

Fig. 4. Growth of the grain having initial radius $r_0 = 10^{-2}$ cm inside some protoplanets. The dotted, dashed, dashed-dotted and solid curves show the configuration for objects with 0.3, 1, 3 and 5 Jupiter masses respectively.

Substituting, the mass of the grain, $m_g = \frac{4}{3}\pi r_g^3 \rho_g$ and the coefficient of viscosity of gas, $\eta = 2.4 \times 10^{-6} T^{2/3}$ g cm^{-1} s^{-1} (DeCampli and Cameron, 1979), we get

$$\left(\lambda \rho r_g^2 \frac{d\zeta}{dt} + 6 a r_g T^{2/3}\right) \frac{d\zeta}{dt} = \frac{4}{3} \frac{G M(\zeta)}{(R-\zeta)^2} r_g^3 \rho_g, \qquad (15)$$

where $a = 2.4 \times 10^{-6}$.

Let us replace the physical variables ζ, $M(\zeta)$, $T(\zeta)$, $P(\zeta)$, t, and r_g by the non-dimensional variables y, q, θ, p, τ, and R_g respectively with the help of the transformations $\zeta = yR$, $M(\zeta) = q(y)M$, $T(\zeta) = \frac{\mu HGM}{kR}\theta(y)$, $P(\zeta) = \frac{GM^2}{4\pi R^4} p(y)$, $t = 10^7 \tau$, and $r_g = r_0 R_g$, where R_g is the non-dimensional radius of the grain, can be obtained from Eq. (8), being given by

$$R_g = 1 + \frac{\lambda M}{16\pi \rho_g r_0 R^2} \int_0^y \frac{p}{\theta} dy \qquad (16)$$

as in non-dimensional form, $\rho = \frac{M}{4\pi R^3} \frac{p}{\theta}$.

Also, Eq. (15) can be written as

$$\frac{p}{\theta}\left(\frac{dy}{d\tau}\right)^2 + A \frac{\theta^{\frac{2}{3}}}{R_g} \frac{dy}{d\tau} - B \frac{q R_g}{(1-y)^2} = 0, \qquad (17)$$

where $A = \frac{24 \times 10^7 \pi a R^2}{r_0 \lambda M} \left(\frac{\mu HGM}{kR}\right)^{\frac{2}{3}}$ and $B = \frac{16 \times 10^{14} \pi G \rho_g r_0}{3\lambda R}$.

Equation (17) gives

$$\frac{dy}{d\tau} = \frac{A\theta^{5/3}\left[\sqrt{1 + \frac{4B}{A^2} \frac{pqR_g^3}{(1-y)^2 \theta^{7/3}}} - 1\right]}{2 R_g p}, \qquad (18)$$

positive sign is taken as $\frac{dy}{d\tau}$ can never be negative. Equation (18), on integration, gives

$$\tau = \int_0^1 F(y, p, q, \theta, R_g) dy, \qquad (19)$$

where

$$F(y, p, q, \theta, R_g) = \frac{2 R_g p}{A\theta^{5/3}\left[\sqrt{1 + \frac{4B}{A^2} \frac{pqR_g^3}{(1-y)^2 \theta^{7/3}}} - 1\right]}. \qquad (20)$$

It is obvious that the integral in Eq. (16) as well as in Eq. (19) cannot be evaluated analytically, so numerical techniques have been taken. Again, because of the singularities the integrations cannot be started right from the surface. However, from a point very near to the surface the integrations can easily be started. A number of parameters are involved in the problem. In our calculation, along with previously used values of the parameters, we have used $\lambda = 2 \times 10^{-2}$, $\rho_g = 3.4$ g cm^{-3} (Helled and Schubert, 2008). It is clear from Eq. (16) that R_g depends on p and

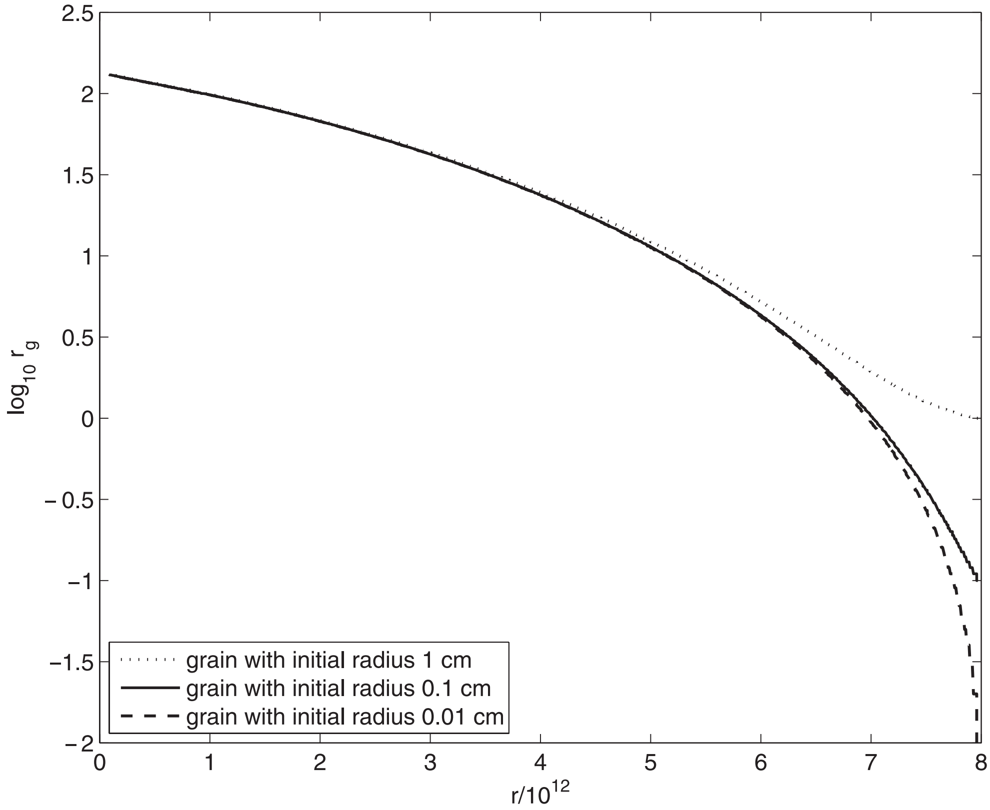

Fig. 5. Growth of grains having different initial radii inside a 5 Jupiter mass protoplanet.

θ. As the values of these variables for different values of y are determined, so numerical integration can then easily be performed. We have evaluated the integral in Eq. (16) by Trapezoidal rule for all the grains considered. The results of our calculations for grain growth are shown in Figs. 4 and 5.

Again, the evaluation of the integral in Eq. (19) depends on $F(y, p, q, \theta, R_g)$, A and B. The values of p, q, θ and R_g for different values of y are now known. Thus, at the y's $F(y, p, q, \theta, R_g)$ can be evaluated. Inserting the values of A and B, we have evaluated the integral in Eq. (19) by Simpson's one-third rule for all the grain sizes considered. The results of our calculation for grains having initial radii 1 cm, 10^{-1} cm and 10^{-2} cm are shown in Table 1.

4. Result, Discussion and Conclusion

We have investigated growth and segregation time of falling grains inside initial gaseous protoplanets formed via disk instability. In doing so, we have determined the distribution of thermodynamic variables inside the protoplanets with masses from 0.3 M_J to 5 M_J and with the distribution we have calculated the growth of grains having different initial sizes (10^{-2} cm $\leq r_0 \leq 1$ cm) as well as calculated their settling times. Figures 1–3 depict temperature, pressure and density distribution respectively inside some gaseous giant protoplanets. It can be seen (Figs. 1, 2) that the central temperature and pressure of the protoplanets increase with increasing mass. The central temperature as calculated by the model can be found to be excellent accordance with Helled and Schubert (2008). But our model predicts a little bit denser protoplanets (Fig. 3) than the ones presented by them. Actually, the distribution of thermodynamic variables inside protoplanets formed by gravitational instability is unknown, and different investigations have been predicted different characteristics, as for example, simulations by Boss (1998b, 2007) predict lower-density and colder protoplanets than the ones found in Mayer *et al*. (2004). Figure 4 depicts the growth of the grain having initial radii of 10^{-2} cm inside some protoplanets. It can be seen from the figure that the grain radius in the core region increases with increasing mass of the protoplanets. The graphs for other values of r_0 agree the trend of the curves presented in Fig. 4 and therefore have not been included. Figure 5 shows the growth of grains inside a 5 Jupiter mass protoplanet with different initial radii. The radii of the grains at a point in the core region having initial radii between 0.01 cm and 1 cm are found to be very similar (Fig. 5). The diagrams of the growth of grains inside other protoplanets considered also look similar to Fig. 5 and therefore have not been included. The sedimentation time as calculated by the model shown in Table 1 in all cases is found to be well within the initial contraction time $\sim 10^5$ years (e.g. Donnison and Williams, 1974; Boss, 1998b; Helled *et al*., 2008; Nayakshin, 2010). Besides r_0, M and R, the segregation time is also dependent on the parameters λ, μ and η. Although we have used particular values for these parameters, the effect of their possible variation on segregation time has also been tested. The results are always found to be in general agreement with those given in Table 1. Thus, it is pertinent to point out from the obtained results presented in Table 1 that a solid core composed almost entirely of refractory material can be formed in a protoplanet due to sedimentation of grains in a reasonably short period of time on astronomical timescale lending support to different numerical codes. It is therefore suggestive that the gaseous planets can form from giant gaseous protoplanets possibly by contraction and sedimentation of solid grains. For terrestrial planets, gaseous envelopes of the protoplanets must be removed by the tidal forces of the Sun. The timescale for the possible removal of the gaseous envelope is equally important with the core formation time as the tidal dispersal time must be longer than the core formation time. The tidal dispersal time as obtained by Donnison and Williams (1975) by both numerical and analytical means is extremely short at the present locations of terrestrial planets and the time is so short that the protoplanets would be disrupted long before any solid core can form inside. In fact, due to the strong tidal effect of the Sun no protoplanet having the obtained distribution of density can be formed at all in the terrestrial region. If the protoplanets migrate inward from outside the Roche limit with heavy cores inside, then the tidal disruptions of the gaseous envelopes may lead to the formation of terrestrial type planets. In that case if the segregation timescale be shorter than the migration timescales, the protoplanets then would have enough time to form cores before they are disrupted by the tidal force of the Sun. It may be mentioned that the timescale for planetary migration is fairly long (e.g., Hahn and Malhotra, 1999; Armitage, 2007) in comparison with our estimated time scale for segregation. Recently, Baruteau *et al.* (2011) and Michael *et al.* (2011) performed numerical simulations of planetary migration of gravitationally unstable discs and showed that giant planets may experience a rapid inward migration ($\sim 10^4$ years) in a GI-driven turbulent disk due to such as spiral arms excited by the planets. Thus, the segregation timescale obtained by the study is quite realistic and also in good agreement with other recently published results with more rigorous treatment of the problem having different numerical codes (e.g. Boss, 1998a; Helled *et al*., 2008; Nayakshin, 2010).

In our investigation, we have assumed the atmosphere is stratified by height due to gravity, it consists of perfect (Clapeyron state equation) gas, the energy equation assumes only the convective heat transfer, and a grain falling in such an atmosphere is assumed to grow gradually due to accretion of material from the atmosphere. In our model, matter is not distributed uniformly. There is variation of parameters due to gravitational stratification. We have used Clapeyron equation (valid for gas at not very high pressure) instead of using a realistic equation of state. In our model, the central pressure of the protoplanets can be found to be below $\sim 2 \times 10^{-2}$ atm. So, the assumption of ideal gas law is reasonable.

In our study, the three very important effects on grain sedimentation time namely, convection motion acting on the grain, turbulent mixing, and destructive collisions discussed in the investigation of Helled *et al.* (2008) and Nayakshin (2010) have not been included. Moreover, in our calculation the effect of radiative heating and the contraction of the gas near the centre due to the increased pressure have not been considered. To make the work simple we have neglected radiation effect. Future development and future perspective of our research work concentrates on the investigation of the grain settling time taking into account the effects to see how the results compare our estimated result.

Acknowledgments. We would like to thank Dr. Shishir Kumer Bhattacharjee and both anonymous referees for comments and suggestions that improved the manuscript.

References

Armitage, P. J., Massive planet migration: theoretical predictions and comparison with observations, *Astrophys. J.*, **665**, 1381–1390, 2007.

Baines, M. J. and I. P. Williams, Growth of interstellar grains, *Nature*, **208**, 1191–1193, 1965.

Baruteau, C., F. Meru, and S.-J. Paardekooper, Rapid inward migration of planets formed by gravitational instability, *Mon. Not. R. Astron. Soc.*, **416**, 1971–1982, 2011.

Boley, A. C., T. W. Hartquist, R. H. Durisen, and S. Michael, The internal energy for molecular hydrogen in gravitationally unstable protoplanetary disks, *Astrophys. J.*, **656**, L89–L92, 2007a.

Boley, A. C., T. W. Hartquist, R. H. Durisen, and S. Michael, Erratum: "The internal energy for molecular hydrogen in gravitationally unstable protoplanetary disks", *Astrophys. J.*, **660**, L175, 2007b.

Boley, A. C., T. Hayfield, L. Mayer, and R.H. Durisen, Clumps in the outer disk by disk instability: Why they are initially gas giants and the legacy of disruption, *Icarus*, **207**, 509–516, 2010.

Boss, A. P., Giant planet formation by gravitational instability, *Science*, **276**, 1836–1839, 1997.

Boss, A. P., Evolution of the solar nebula. iv. Giant gaseous protoplanet formation, *Astrophys. J.*, **503**, 923–937, 1998a.

Boss, A. P., Formation of extrasolar giant planets: Core accretion or disk instability?, *Earth Moon Planets*, **81**, 19–26, 1998b.

Boss, A. P., Evolution of the solar nebula. vi. Mixing and transport of isotropic heterogeneity, *Astrophys. J.*, **616**, 1265–1277, 2004.

Boss, A. P., Testing disk instability models for giant planet formation, *Astrophys. J.*, **661**, L73–L76, 2007.

Cai, K., R. H. Durisen, S. Michael, A. C. Boley, A. C. Mejia, M. K. Pickett, and P. D'Alessio, The effects of metallicity and grain size on gravitational instabilities in protoplanetary disks, *Astrophys. J.*, **636**, L149–L152, 2006a.

Cai, K., R. H. Durisen, S. Michael, A. C. Boley, A. C. Mejia, M. K. Pickett, and P. D'Alessio, Erratum: "The effects of metallicity and grain size on gravitational instabilities in protoplanetary disks", *Astrophys. J.*, **642**, L173, 2006b.

Cameron, A. G. W., Physics of the primitive solar accretion disk, *Moon Planets*, **18**, 5–40, 1978.

Cha, S.-H. and S. Nayakshin, A numerical simulation of a "super-Earth" core delivery from ~100 AU to ~8 AU, *Mon. Not. R. Astron. Soc.*, **415**, 3319–3334, 2011.

DeCampli, W. M. and A. G. W. Cameron, Structure and evolution of isolated giant gaseous protoplanets, *Icarus*, **38**, 367–391, 1979.

Donnison, J. R. and I. P. Williams, The evolution of Jupiter from a protoplanet, *Astrophys. Space Sci.*, **29**, 387–396, 1974.

Donnison, J. R. and I. P. Williams, The effects of tidal forces on the stability and dispersal rates of a protoplanet, *Mon. Not. R. Astron. Soc.*, **172**, 257–269, 1975.

Hahn, J. M. and R. Malhotra, Orbital evolution of planets embedded in a massive planetesimal disk, *Astron. J.*, **117**, 3041–3053, 1999.

Helled, R. and P. Bodenheimer, The effects of metallicity and grain growth and settling on the early evolution of gaseous protoplanets, *Icarus*, **211**, 939–947, 2011.

Helled, R. and G. Schubert, Core formation in giant gaseous protoplanets, *Icarus*, **198**, 156–162, 2008.

Helled, R., A. Kovetz, and M Podolak, Settling of small grains in an extended protoplanet, *Bull. Am. Astron. Soc.*, **37**, 675, 2005.

Helled, R., M. Podolak, and A. Kovetz, Grain sedimentation in a giant gaseous protoplanet, *Icarus*, **195**, 863–870, 2008.

Kuiper, G. P., On the origin of the solar system, *Proc. Natl. Acad. Sci.*, **37**, 1–14, 1951.

Mayer, L., T. Quinn, J. Wadsley, and J. Stadel, Formation of giant planets by fragmentation of protoplanetary disks, *Science*, **298**, 1756–1759, 2002.

Mayer, L., T. Quinn, J. Wadsley, and J. Stadel, The evolution of gravitationally unstable protoplanetary disks: Fragmentation and possible giant planet formation, *Astrophys. J.*, **609**, 1045–1064, 2004.

McCrea, W. H. and I. P. Williams, Segregation of materials in cosmogony,

Proc. R. Soc., **A287**, 143–164, 1965.
Michael, S., R. H. Durisen, and A. C. Boley, Migration of gas giant planets in gravitationally unstable disks, *Astrophys. J.*, **737**, L42–L47, 2011.
Movshovitz, N. and M. Podolak, The opacity of grains in protoplanetary atmospheres, *Icarus*, **194**, 368–378, 2008.
Nayakshin, S., A new view on planet formation, arXiv:1012.1780, 2010.
Paul, G. C., J. N. Pramanik, and S. K. Bhattacharjee, Structure of initial protoplanets, *Int. J. Mod. Phys. A*, **23**, 2801–2808, 2008.
Paul, G. C., S. K. Bhattacharjee, and J. N. Pramanik, Grain sedimentation time in a gaseous protoplanet, *Earth Moon Planets*, **108**, 87–94, 2011.
Pickett, B. K., P. Cassen, R. H. Durisen, and R. Link, The effects of thermal energetics on three-dimensional hydrodynamic instabilities in massive protostellar disks. II. High-resolution and adiabatic evolutions, *Astrophys. J.*, **529**, 1034–1053, 2000.
Podolak, M., The contribution of small grains to the opacity of protoplanetary atmospheres, *Icarus*, **165**, 428–437, 2003.
Urey, H. C., Chemical evidence relative to the origin of the solar system, *Mon. Not. R. Astron. Soc.*, **131**, 199–223, 1966.
Williams, I. P. and M. J. Handbury, Segreation of the heavy elements in the solar system, *Astrophys. Space Sci.*, **30**, 215–223, 1974.

G. C. Paul (e-mail: pcgour2001@yahoo.com), S. Datta, J. N. Pramanik, and M. M. Rahman