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Were planetesimals formed by dust accretion in the solar nebula?

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The growth of meter-sized bodies in the solar nebula by dust accretion is examined. The meter-sized bodies have velocity about 50 m/s relative to the gas and small dust aggregates. When a small dust aggregate hits a meter-sized body, the aggregate breaks into dust monomers. These monomers accrete onto the body after several bouncing as proposed by Wurm *et al., Icarus* (2001), if the mean free path of the gas molecules is larger than the radius of the body. On the other hand, the monomers never hit the surface of the body again, if the body is much larger than the mean free path of the molecules. The sizes of bodies would be limited to the order of 10 times the mean free path. Kilometer-sized planetesimals were hardly formed by dust accretion in the region within 5 AU from the sun where the mean free path is less than 1 m. The planetesimals were probably formed by the gravitational instabilities in this region.

Key words: Planets, solar system, solar nebula, planetesimals.

1. Introduction

Terrestrial planets are considered to have been formed through continuous collisional coagulations of planetesimals due to mutual gravitational force (Safronov, 1969; Hayashi *et al.*, 1985). The collisional coagulation due to mutual gravity occurs for planetesimals whose radii are $\gtrsim$1 km and the escape velocities are $\gtrsim$1 m/s. The initial radii of solid dust particles (called as monomers in the following) in the protoplanetary disk are probably on the order of 1 μm. Thus, there should have been processes other than the gravitational coagulation for solid bodies to grow their sizes from $\sim$1 μm to $\sim$1 km.

Formerly, fragmentation of a thin dust layer around the midplane of the protoplanetary disk due to self-gravity was considered to be the most promising process of formation of a lot of km-sized planetesimals (Safronov, 1969; Goldreich and Ward, 1973; Coradini *et al.*, 1981; Sekiya, 1983). However, shear-induced turbulence in the dust layer may prevent the dust aggregates from settling sufficiently to reach the critical density of the gravitational fragmentation (Weidenschilling, 1980, 1984; Cuzzi *et al.*, 1993; Weidenschilling and Cuzzi, 1993; Sekiya, 1998).

Recently, an interesting process of growth of dust aggregates in the nebular gas was proposed by Wurm *et al.* (2001a, b). When a small dust aggregate hits a large dust aggregate with a velocity $\gtrsim$1 m/s, the former would be disrupted into monomers; they are subsequently dragged by the gas flow toward the large aggregate, and after bouncing several times on the surface of the large aggregate, they eventually accrete onto the surface. Wurm *et al.* (2001a, b) have shown from their experiments that this process is very efficient so that a small dust aggregate can accrete onto a larger body even if the collisional velocity is $\gtrsim$1 m/s. The target which was used to simulate a large aggregate in their experiments had a size comparable to the mean free path of gas molecules; that is, their experiments were done in the transition regime between the continuous fluid and the free molecule flow. Thus, bodies in the solar nebula are expected to grow until their sizes become on the order of the mean free path through the above mentioned process. However, it is not known whether the bodies can grow further to sizes much larger than the mean free path through the accretion of the dust aggregates and monomers.

In this paper, we consider the growth of a spherical body much larger than the mean free path, but much smaller than 1 km; thus, the coagulation due to gravity does not occur. Then the flow around the body is obtained by hydrodynamic equations. In a flow around a body much larger than the mean free path, gas molecules do not move ballistically. They rather flow hydrodynamically around the body. After a dust aggregate collides and breaks up into monomers, they may be dragged away from the sphere by the gas flow. Thus it is expected that the gas drag prevents the accretion of small aggregates onto larger bodies, as already pointed out by Wurm *et al.* (2001a) in their last paragraph. In order to elucidate this process, we solved trajectories of small dust aggregates and monomers in hydrodynamic flow around a spherical body much larger than the mean free path.

Since the mean free path of gas molecules $l_g \gtrsim 1$ m in the outer solar nebula (*i.e.* the heliocentric distance $r \gtrsim 5$ AU), the hydrodynamic approach is not relevant to bodies with $\lesssim$100 m for which the collisional coagulation due to mutual gravity can be neglected. Thus, we restrict ourselves to treat the inner solar nebula ($r \lesssim 5$ AU) in this paper.

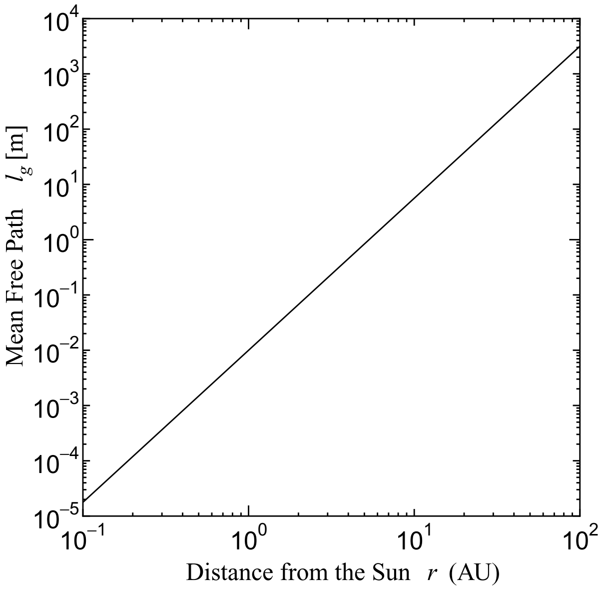

Fig. 1. The mean free path of gas molecules in the minimum mass solar nebula.

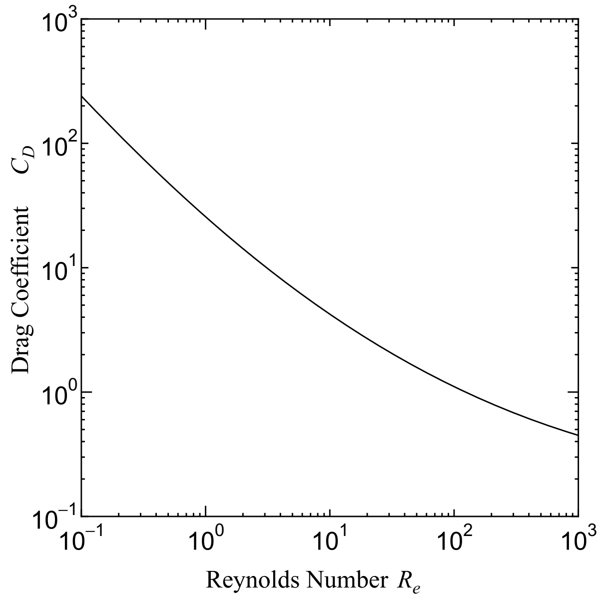

Fig. 2. The gas drag coefficient as a function of the Reynolds number.

In Section 2, the model used in this paper is described, and the velocity of a meter-sized body and the Reynolds number of the flow around the body are obtained. In Section 3, the trajectories of small dust aggregates and monomers around a large target body is calculated. In Section 4, implications on planet formation from our results are discussed. In Section 5, conclusions are summarized.

2. The Velocity of a Meter-Sized Spherical Body in the Nebular Gas and the Reynolds Number of the Flow around the Body

We use the minimum mass model (Hayashi, 1981; Hayashi *et al.*, 1985) as a representative model of the solar nebula. The gas density around the midplane is given by

$$\rho_g = 1.4 \times 10^{-6} (r/\mathrm{AU})^{-11/4}\ \mathrm{kg/m^3}. \tag{1}$$

The mean free path of the gas molecules around the midplane of the nebula is given by (see Fig. 1)

$$l_g = [2^{1/2}\sigma_{mol}(\rho_g/\mu_{mol} m_H)]^{-1} = 1.0 \times 10^{-2} (r/\mathrm{AU})^{11/4}\ \mathrm{m}, \tag{2}$$

where m_H is the mass of a hydrogen atom, and σ_{mol} and μ_{mol} are the mean cross section and the mean molecular weight of molecules. We take $\sigma_{mol} = 2 \times 10^{-19} \mathrm{m}^2$ and $\mu_{mol} = 2.34$, respectively.

In this paper, we restrict ourselves to the case where the dust density, *i.e.* the total mass of dust aggregates and monomers in unit volume of the nebula, is much smaller than the gas density. Then the revolution velocity of the nebular gas v_g is slightly slower than the circular Kepler velocity v_K due to outward pressure gradient; $v_g = (1 - \eta) v_K$, where,

$$\eta = -\frac{1}{2r\Omega_K^2 \rho_g} \frac{\partial P_g}{\partial r}, \tag{3}$$

where P_g is the gas pressure and Ω_K is the circular Keplerian angular velocity (Adachi *et al.*, 1976; Weidenschilling, 1977; Nakagawa *et al.*, 1986).

We consider whether the growth of a spherical body (hereafter called SB) much larger than the mean free path by accreting small dust aggregates and monomers is possible. The gas flow around a SB is a classical issue and a number of experiments (Taneda, 1956; Magarvey and Bishop, 1961; Goldburg and Florsheim, 1966; Nakamura, 1976) as well as numerical simulations (Rimon and Cheng, 1969; Kalro and Tezduyar, 1998; Lee, 2000) have been done. The flow is characterized by the Reynolds number $R_e = 2Rv_\infty/\nu$, where R is the radius of the SB, v_∞ is the upstream velocity, and ν is the kinematic viscosity. The flow is steady and axisymmetric as long as $R_e < 130$. We restrict ourselves to this regime in this paper. The drag force on SB is usually written in the form

$$F_D = \frac{1}{2} C_D \rho_g v_\infty^2 \pi R^2, \tag{4}$$

where C_D is a non-dimensional coefficient (the drag coefficient). As shown in Fig. 2, C_D is a function of R_e, which is obtained by experiments and/or numerical simulations (*e.g.*, Rimon and Cheng, 1969). The friction time of SB is given by

$$t_{fSB} = (4\pi/3) R^3 \rho_{SB} v_\infty / F_D, \tag{5}$$

where ρ_{SB} is the density of SB.

The motion of a body in the solar nebula is determined by the gravitational force of the sun as well as other bodies, the gas drag force, and the effect of collision with other bodies. We here neglect the random velocity excited by the gravitational force of other bodies, because we consider the stage before km-sized planetesimals are formed and treat bodies with radii $\lesssim$ 10 m. We also neglect the effect of collisions, since the collisions between large bodies under consideration are not so frequent. In that situation, Adachi *et al.* (1976) and Weidenschilling (1977) investigated the motion of solid particles in the solar nebula. The radial and azimuthal components of the velocity of SB relative to the nebular gas, v_r and $v_\phi - v_g$, respectively, are given by

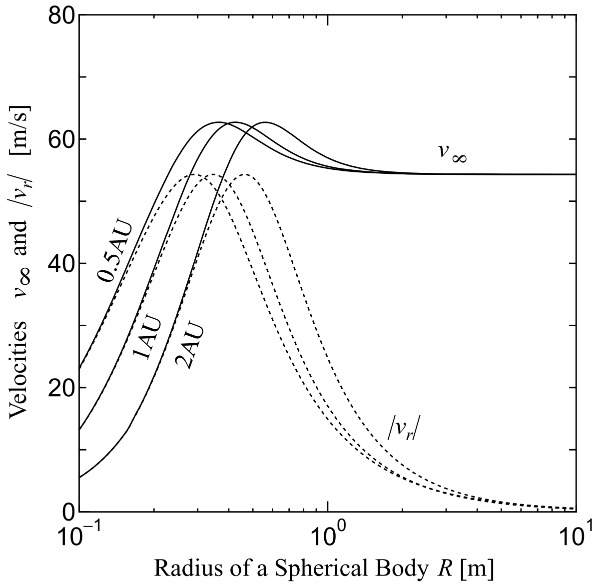

Fig. 3. The velocity of a solid sphere with radius R for $r = 0.5$, 1, and 2 AU. The solid curves show the absolute value of the velocity relative to the gas, v_∞, and the dashed curves show the radial infall velocity toward the sun, $|v_r|$.

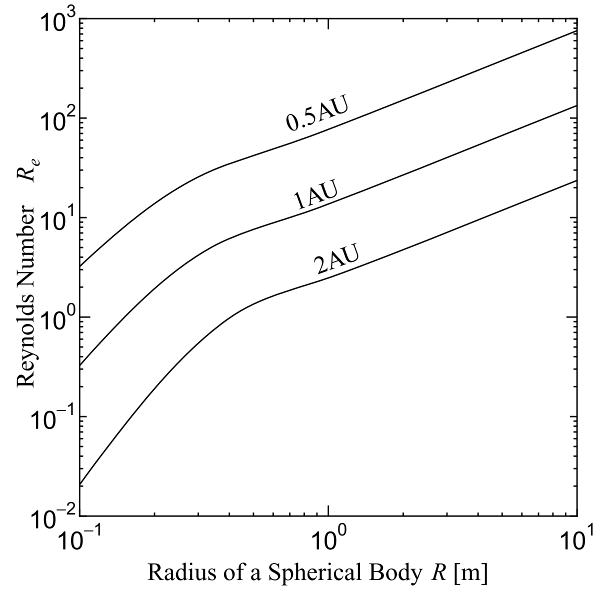

Fig. 4. The Reynolds number of the gas flow around a solid sphere with radius R, for $r = 0.5$, 1, and 2 AU.

Eqs. (5.5) to (5.7) and (5.9) of Adachi *et al.* (1976):

$$v_r = -\frac{2(\Omega_K t_{fSB})^{-1}}{1+(\Omega_K t_{fSB})^{-2}} \eta v_K, \tag{6}$$

and

$$v_\phi - v_g = \frac{1}{1+(\Omega_K t_{fSB})^{-2}} \eta v_K. \tag{7}$$

The magnitude of the relative velocity is

$$\begin{aligned} v_\infty &= \left[v_r^2 + (v_\phi - v_g)^2\right]^{1/2}, \\ &= \frac{[1+4(\Omega_K t_{fSB})^{-2}]^{1/2}}{1+(\Omega_K t_{fSB})^{-2}} \eta v_K. \end{aligned} \tag{8}$$

Equations (4), (5) and (8) are coupled each other (note that C_D is also a function of v_∞ through R_e). The values of v_r and v_∞ are drawn in Fig. 3 and R_e in Fig. 4 as functions of R for $r = 0.5$, 1 and 2 AU. Note that values in these figures are calculated with the assumption of the continuous fluid, which is good for $R \gtrsim 100 l_g$ (= 0.15 m at 0.5 AU, 1.0 m at 1 AU, and 7 m for 2 AU). The values for $l_g \lesssim R \lesssim 100 l_g$ should be considered as rough approximations. Figure 4 shows that R_e is on the order of 1 to 100 for a meter-sized spherical body. The values of v_∞ given by Eq. (8) will be used to estimate the incident gas velocity relative to a SB as well as the collision velocity of a dust aggregate with a SB in the next section, and the value of v_r given by Eq. (6) will be used to estimate the infall time scale of a SB in Section 4.

3. Particle Trajectories Dragged by the Gas Flow

As for gas flows around the sphere, the representative value of the Reynolds number is taken $R_e = 50$, according to the above result. The following results are not sensitive to the value of R_e. The numerical code used in solving the gas flow field $\boldsymbol{v}_g$ for $R_e = 50$ is same as written in Takeda *et al.* (1985) and Takeda (1988), but we neglected the gravity of the body. Although this is a code for a compressible flow, we solved the case where the Mach number is as small as 0.06 and the flow is almost incompressible. We take a coordinate system where the center of SB is at the origin. Gas flows in the z-direction from $z = -\infty$ with the velocity v_∞ given by Eq. (8) above.

The equation of motion of a dust monomer or a dust aggregate is written

$$d\boldsymbol{v}_d/dt = -(\boldsymbol{v}_d - \boldsymbol{v}_g)/t_f \tag{9}$$

where $\boldsymbol{v}_d$ and $\boldsymbol{v}_g$ are dust and gas velocities, respectively, and t_f is the friction time of the dust monomer or the dust aggregate. If the dust monomer is spherical with radius r_{mon} much smaller than l_g, the friction time is given by the Epstein Law:

$$t_f = \rho_{mat} r_{mon} / (\rho_g c_{mol} \delta p), \tag{10}$$

where ρ_{mat} is the material density of the dust particle, c_{mol} is the mean velocity of the gas molecules, and δp is the momentum transfer coefficient ($\delta p = 1$ for specular reflection). For an aggregate of dust monomers (Blum *et al.*, 1996; Blum and Wurm, 2000; Wurm *et al.*, 2001a),

$$t_f = 3 m_{ag} / (4 < \sigma_{ag} > \rho_g c_{mol} \delta p) \tag{11}$$

where m_{ag} is the aggregate mass, $< \sigma_{ag} >$ is the geometric cross section (*i.e.*, the mean projected area). In the following, we use non-dimensional variables normalizing the distance by R and the velocity by v_∞, and the time by R/v_∞. The non-dimensional friction time is written by $T_f = t_f v_\infty / R$. The non-dimensional coordinates are written by large characters $(X, Y, Z) = (x/R, y/R, z/R)$. The non-dimensional distance from Z-axis is written by $\Pi = (X^2 + Y^2)^{1/2}$.

The trajectories of a small dust aggregate are characterized by T_f and R_e. The trajectories of small dust aggregates, whose initial positions are $Z_0 = -10$ and $\Pi_0 = 0.1$, 0.2, 0.3,...,1.0, and the initial velocity is same as the gas velocity, are drawn in Figs. 5, 6 and 7 for $T_f = 10$, 1.0 and 0.1,

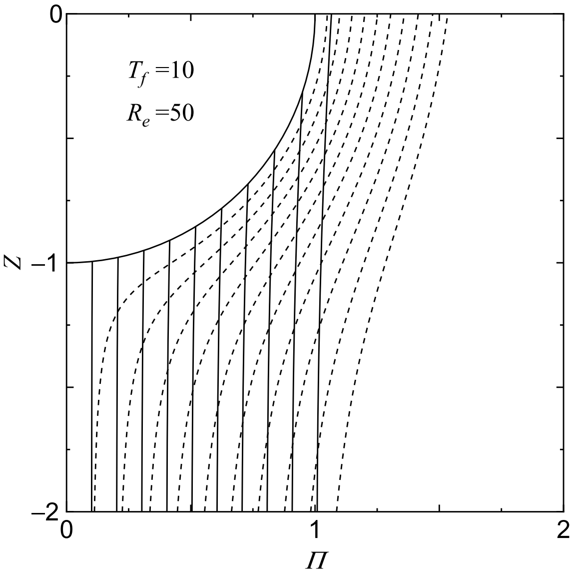

Fig. 5. Trajectories of small dust aggregates with non-dimensional friction time $T_f = 10$ in the gas flow with $R_e = 50$. The stream lines of gas are shown by dashed curves.

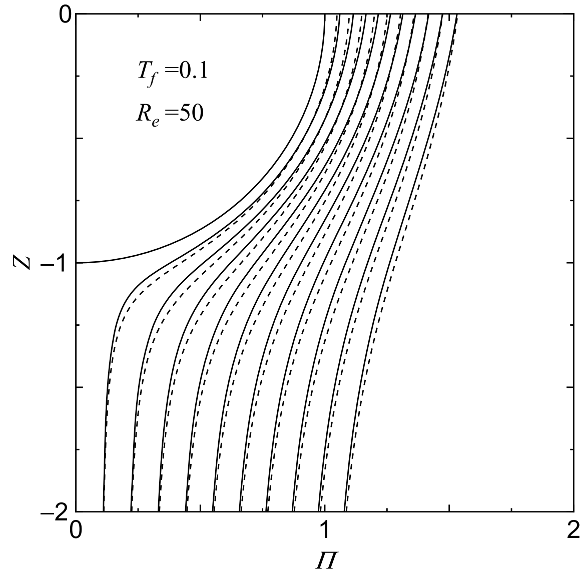

Fig. 7. Same as Fig. 5, but for $T_f = 0.1$.

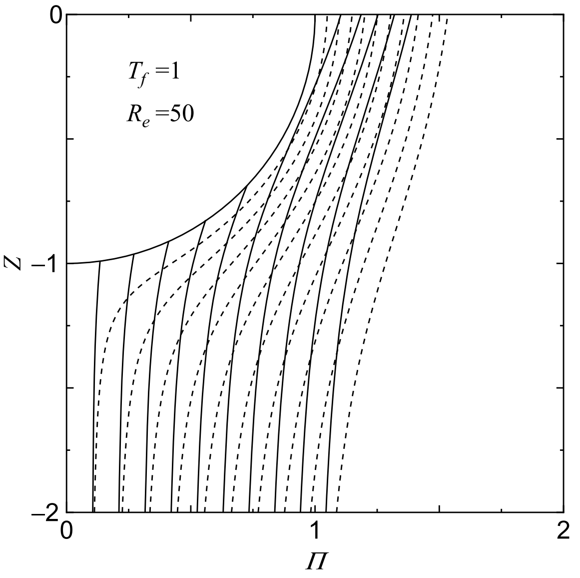

Fig. 6. Same as Fig. 5, but for $T_f = 1$.

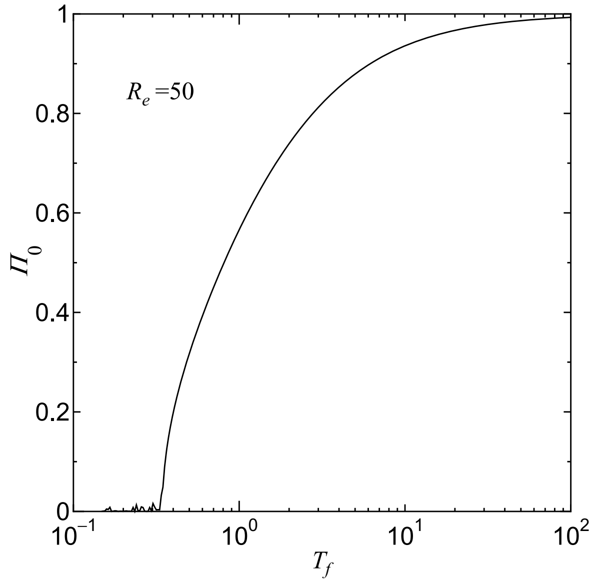

Fig. 8. The maximum value of the impact parameter Π_0 for collision with SB as a function of T_f.

respectively. The Reynolds number is $R_e = 50$. Numerical integration of Eq. (9) for a given $\boldsymbol{v}_g$ is made by using 8-th order Runge-Kutta method (Butcher, 1987). As seen from Fig. 5, the dust aggregates with $T_f = 10$ are hardly affected by the gas flow. On the other hand, the dust aggregates with $T_f = 0.1$ are nearly completely dragged by the gas flow and hardly hit the large sphere as seen from Fig. 7. For the dust aggregates with $T_f = 1.0$, the trajectories are moderately affected by the gas drag and aggregates with impact parameter $\Pi_0 \lesssim 0.5$ hit the sphere as seen from Fig. 6. The maximum impact parameter for the collision is drawn as a function of T_f in Fig. 8 for $R_e = 50$. It is seen that dust aggregates can collide with a large sphere as long as $T_f \gtrsim 1$. This result is not sensitive to the value of R_e.

For a spherical monomer with the material density ρ_{mat}, the non-dimensional friction time is written as

$$T_f = r_{mon}\rho_{mat}v_\infty/(\delta p \rho_g c_{mol} R)$$
$$= 50\,\delta p^{-1}\left(\frac{r}{1\ \mathrm{AU}}\right)^3\left(\frac{v_\infty}{50\ \mathrm{m/s}}\right)$$
$$\cdot\left(\frac{R}{1\ \mathrm{m}}\right)^{-1}\left(\frac{\rho_{mat}}{3\times10^3\mathrm{kg\ m^{-3}}}\right)\left(\frac{r_{mon}}{1\ \mu\mathrm{m}}\right). \quad (12)$$

For a two-dimensional fluffy aggregate, $m_{ag}/ < \sigma_{ag} >\sim r_{mon}\rho_{mat}$ and the value of T_f has the same order of magnitude as that of the monomer as seen from Eqs. (10) and (11). For a compact aggregate, the value of T_f is larger. Thus inequality $T_f \gtrsim 1$ is always satisfied as long as $r \geq 1$ AU, $r_{mon} \geq 1\ \mu$m and $R \leq 10$ m. Although inequality $T_f \gtrsim 1$ is violated for the two-dimensional fluffy aggregate

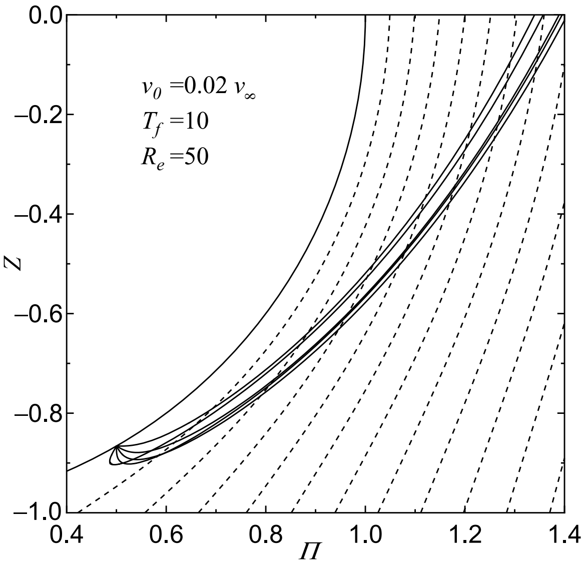

Fig. 9. Trajectories of monomers after break up on the surface of SB for $v_0 = 0.02v_\infty$, $T_f = 10$, and $R_e = 50$. The stream lines of gas are shown by dashed curves.

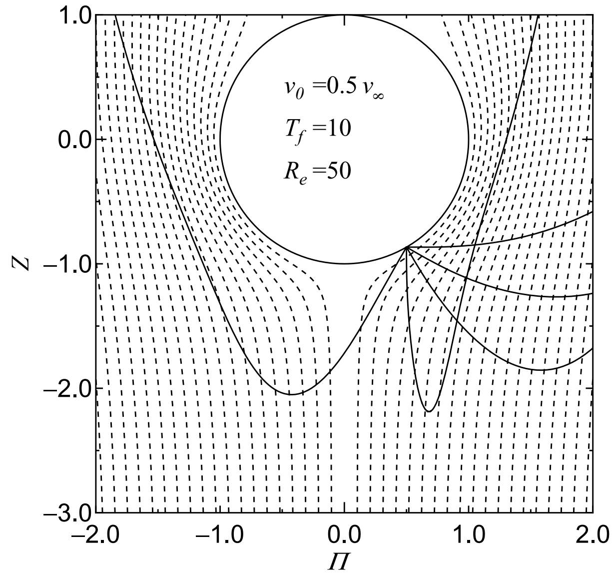

Fig. 11. Same as Fig. 9, but for $v_0 = 0.5v_\infty$.

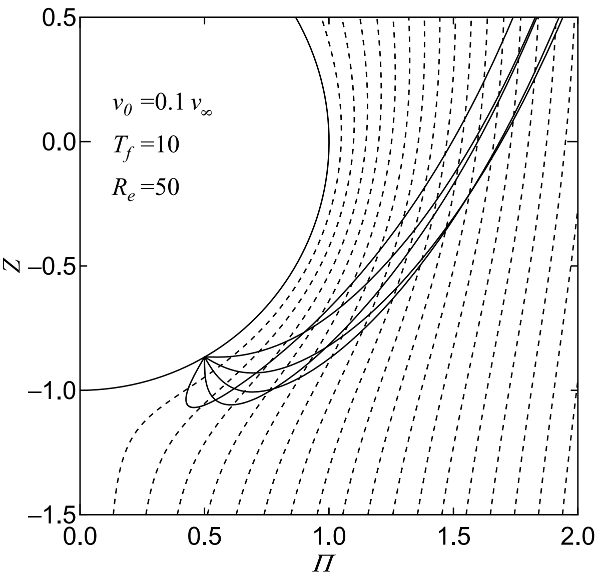

Fig. 10. Same as Fig. 9, but for $v_0 = 0.1v_\infty$.

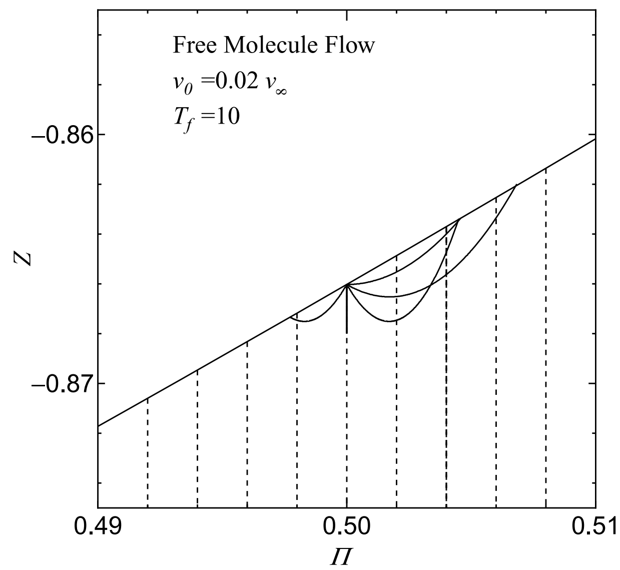

Fig. 12. Trajectories of monomers after break up on the surface of SB in free molecule flow with $v_0 = 0.02v_\infty$ and $T_f = 10$. The stream lines of gas are shown by dashed lines.

if $r << 1$ AU, compaction of dust aggregate would increase $m_{ag}/ < \sigma_{ag} >$ and the inequality would be satisfied. Thus, small dust aggregates would always hit large aggregates.

The collision velocity of dust aggregates with SB is on the order of $v_\infty \sim 50$ m/s, as long as $T_f \gtrsim 1$. Then the small aggregate would be disrupted to monomers, which would bounce immediately (Dominik and Tielens, 1997; Blum and Wurm, 2000; Wurm *et al.*, 2001a, b). We obtained the trajectories of these monomers assuming three values of the initial bounce velocity: $v_0 = 0.02v_\infty$, $0.1v_\infty$ and $0.5v_\infty$, *i.e.* $\sim$1 m/s, 5 m/s and 25 m/s, respectively. The non-dimensional friction time is assumed $T_f = 10$, *i.e.* $R = 5$ m/s for $r_{mon} = 1$ μm and $\rho_{mat} = 3 \times 10^3$ kg m^{-3} at $r = 1$ AU. The initial position is set to be at $\Pi = 0.5$. The initial angles between the velocity vectors and the normal of the surface are taken 0°, ±30°, ±60°. Figures 9 to 11 show the results for $v_0 = 0.02v_\infty$, $0.1v_\infty$ and $0.5v_\infty$, respectively. It is seen that all the monomers are swept away by the gas flow. We have made additional calculations for various values of parameters v_0, T_f, initial positions on SB, and initial angles of the velocity vector. In all the cases, monomers are well dragged by the gas which flows away from SB, and no monomers hit the surface of SB again.

For comparison, the trajectories in free molecule flow are drawn in Figs. 12 to 14, for $v_0 = 0.02v_\infty$, $0.1v_\infty$ and $0.5v_\infty$, respectively. It is seen that the monomers, which are launched from the surface of SB after a break up on the surface, return the surface again as long as $v_0 \lesssim 0.1v_\infty$.

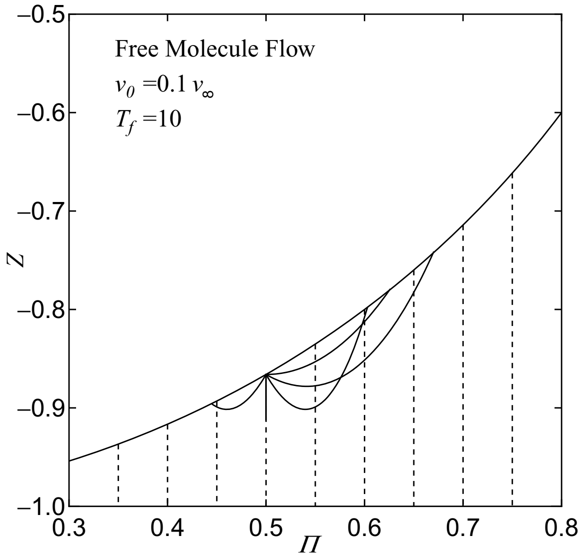

Fig. 13. Same as Fig. 12, but for $v_0 = 0.1v_\infty$.

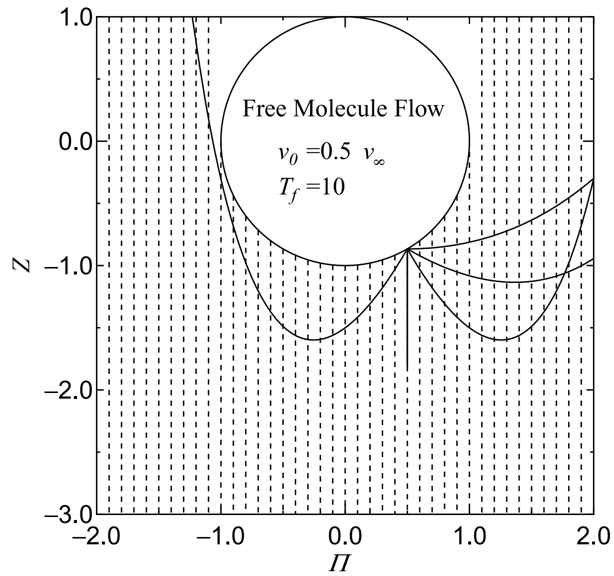

Fig. 14. Same as Fig. 12, but for $v_0 = 0.5v_\infty$.

4. Discussion

Here we discuss the growth of SBs in the solar nebula. If there are meter-sized SBs, they have velocities ~50 m/s relative to the nebular gas and small dust aggregates. Small dust aggregates hit the surface of SB with velocities ~50 m/s, and break up into dust monomers (Dominik and Tielens, 1997; Blum and Wurm, 2000). If $R \lesssim l_g$, some monomers hit the surface of SB again as shown in Figs. 12 and 13. If the velocity of the second collision is $\lesssim$1 m/s, the monomer sticks to SB (Heim *et al.*, 1999; Poppe *et al.*, 2000; Wurm *et al.*, 2001a, b). Else if the collision velocity is $\gtrsim$1 m/s, the monomer bounces on the surface of SB, and loses some amount of the kinetic energy due to inelasticity. After several bouncing and losing energies, the monomer eventually sticks to SB. Thus SB whose radius $R \lesssim 3l_g$ grows by accreting monomers after collisional break up of dust aggregates (Wurm *et al.*, 2001a, b). On the other hand, if $R \gtrsim 100l_g$, the flow around SB is described by the continuous hydrodynamic flow. In this case, trajectories of monomers are as shown in Figs. 9 to 11, and they never hit the surface of SB again. Thus, such SB would not grow by accreting dust aggregates and monomers. It is then expected that the maximum radius of bodies made by dust accretion due to non-gravitational forces is on the order of $10l_g$ (see Fig. 1 as for the value of l_g of the minimum mass solar nebula). In order to determine the maximum size of SB precisely, the detailed analysis based on the Boltzmann equation would be needed, which is beyond the scope of this paper.

It is interesting to note that the maximum size of SB in the asteroid region would be ~1 m (see Fig. 1) for which the velocity towards the sun $|v_r|$ has the maximum value as large as several tens m/s (see Fig. 3). The time scale of infall from 2 AU to 1 AU is about 100 yrs for SB with 0.4 m. Thus it is possible that the shortage of matter in the asteroid region is due to effective infall, although it is usually believed that the giant planets' gravity cause the removal of planetesimals from the region (Wetherill, 1992; Chambers and Wetherill, 2001).

In this paper, we have shown that the formation of km-sized planetesimals through the accretion of dust aggregates (Wurm *et al.*, 2001a) is difficult to occur in the inner solar nebula ($r \lesssim 5$ AU) where the mean free path is less than 1 m (see Fig. 1). We cannot exclude the possibility of the planetesimal formation through dust accretion in the outer solar nebula ($r \gtrsim 5$ AU) by our simulations which assumes the continuous flows around SBs. Particularly, in the outermost part of the solar nebula where comets were formed ($r \gtrsim 30$ AU), planetesimals were probably formed through collisional coagulations (Weidenschilling, 1997). Elaborate numerical simulations of the flow around SBs using the Boltzmann equation as well as experiments in the transition regime between the free molecular flow and the continuous flow should be done in future in order to elucidate the dust accretion processes by SBs in the outer solar nebula.

Now, we consider how planetesimals were formed in the inner solar nebula. Sekiya (1998) have shown that the increase of the dust/gas surface density ratio suppresses the shear-induced turbulence. Thus, the gravitational instability might occur if there is a mechanism to concentrate dust to some locations (Youdin and Shu, 2002). One possibility is the above mentioned effective infall of meter-sized body from asteroid region, which supplies some additional mass to the region around 1 AU. Another possibility is the concentration of dust aggregates by eddies which might be persistent in the solar nebula like Jovian great red spot (Barge and Sommeria, 1995; Tanga *et al.*, 1996; Chavanis, 2000; Godon and Livio, 2000; Marcos and Barge, 2001; Klahr and Bodenheimer, 2003). Further, the UV irradiation (Shu *et al.*, 1993) and the magneto-rotational instability around the disk surface region (Gammie, 1996) lead the loss of the gas from the nebula leaving the dust around the midplane, which increases the dust/gas surface density ratio. Recently, Ishitsu and Sekiya (2003) have shown that the tidal force has the effect to suppress the shear instability, which also act for the gravitational instability. Anyway, more works should be done in future to elucidate the formation mechanism of planetesimals.

5. Conclusion

In this paper, the growth of meter-sized bodies in the solar nebula by dust accretion is examined. Meter-sized bodies have velocity about 50 m/s relative to the gas. Small dust aggregates in the nebula have almost same velocity with the gas. Thus, the incident velocity of a small dust aggregate toward a meter-sized body is about 50 m/s. When the small dust aggregate hits a meter-sized body, the aggregate breaks into μm-sized dust monomers. These monomers accrete onto the body after several bouncing as proposed by Wurm *et al.* (2001a), if the mean free path of the gas molecules is larger than the radius of the body. On the other hand, hydrodynamic flow around the body prevents monomers from hitting the surface of the body again and the body will not grow further, if the body is much larger than the mean free path of the molecules. Thus, the sizes of bodies are limited to the order of 10 times the mean free path. Kilometer-sized planetesimals were hardly formed by dust accretion within 5 AU from the sun where the mean free path of gas molecules are smaller than 1 m; they were probably formed by the gravitational instabilities.

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