When and why formation of large bodies in circumstellar discs could take place?

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Abstract. We outlined the scenario of the planetary system formation, where large bodies are formed on the stage of massive discs. On this stage the whole of factors: chemical composition, chemical catalytic reactions, the disc self-gravitation, the increased ratio of solids to gas surface density, adiabatic gas cooling provides favorable conditions for gravitational instabilities development. Gravitational instabilities in multiphase medium can lead to planetesimal and planetary embryo formation.

1 Introduction

Planetary formation processes are commonly considered for low-massive and medium massive protoplanetary discs. Structure formation on early stages of disc evolution are little-studied. We investigate processes in massive discs, being motivated by the following statements.

1. Chemical composition of the gas-dust medium that forms the disc and the star. In such composition after hydrogen, helium and water the organic compounds form the large portion. Presence of the organic compounds drastically changes collisional dynamics of the solids in the discs and their upper size defined by aggregation.

2. The inorganic compounds of the solids are active in chemical reactions of Fisher-Tropsh synthesis $CO + H_2 \rightarrow C_xH_y + H_2O$, which decreases under favorable conditions the concentration of CO. Therefore the ratio $CO/H_2 \sim 10^{-4}$ true for the molecular clouds can be decreased for the circumstellar discs. So when the mass of the disc is estimated by means of CO concentration measuring, it can be underestimated.

3. Massive self-gravitating disc where gravitational instability development could take place can be formed as a result of Jeans instability in molecular cloud and following fragment collapse.

   - During the solid subdisc formation the part of the gas can leave the gisc, abandoning the solids sedimentating in the equatorial plane. As a result of such gas outflow the ratio of dust to gas surface density in the subdisc can be significantly large than 0.01.

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- The temperature of the gas in the disc can be decreased on the later stages of collapse that forms the disc and the protostar. After first 500 thousand of years the gas changes the direction of their motion and moves mainly from the star, providing the conditions for adiabatic cooling.

2 Physical models of initial stages of circumstellar disc formation

The disc forms simultaneously with a protostar, following the gravitational collapse of gas in the molecular cloud [1]. In the first stage (which lasts up to 100,000 years), a protostar forms; this consists mainly of hydrogen and helium, and has a mass of about one tenth of the solar mass.

The massive gas-dust disc is formed by the collision of the opposing gas streams. The gas streaming during the molecular cloud collapse is supersonic. The infalling gas streams collide and produce the diverging shock waves that decelerate the gas streams velocity [2]. Between a pair of shock waves the gas density is higher than its extreme value for a single shock wave. When the flow rate of collapsing gas decreases in the end of the star formation stage, the shock waves diverge from the disc plane. Now the gas can leave the disc. Fast diminution of its flow provides conditions for the fast gas expansion which is followed up with its cooling.

The molecular cloud dust moves together with the gas. During the gas compression behind the shock waves the dust grains grow in size as a result of heavy molecular absorption and coagulation. The molecules are adsorbed according to their sublimation temperature. The dust grains can grow in size in accretion disc, settle on the disc plane and form their own subdisc [3]. Due to the subdisc gas expansion in outside flow the relation of solid density to gas density increases in contrast to the molecular clouds, where dust constitutes 1-2 per cent of the mass.

The protostar increases its mass up to the star mass due to accretion from the disc and the residues of the surrounding molecular cloud (see Fig.1). Fig.1 shows the time changes of the mass of the protostar and the disc during the molecular cloud collapse. The calculation of collapse of the Bonnor-Ebert sphere with initial solid-body rotation was performed for isothermal model by Snytnikov and Stadnichenko [4].

Alteration of the disc mass is defined by the flows: (a) falling to the disc from the cloud, (b) accreting from the disc to the protostar, (c) leaving the disc, e.g., in jets. By the time discs become observable (1-3 million years), their masses have decreased to 1 per cent of the host star mass. Inside the period between protostar and young star a stage of massive disc exists, when the mass of the disc and the mass of the central body are comparable. Over the course of the next 60-100 million years, the circumsolar disc evolves to a state similar to that currently present in our own Solar System.

3 Physical and chemical conditions for dust growth

The formation of planets in circumstellar discs proceeds via the growth of solids; nanometer-sized dust in molecular clouds transforms into planets with radii of some thousands of kilometres.

The growth of dust grains via coagulation depends on chemical composition. Usually ice, silicates and iron are mentioned as dust compounds. But due to the cosmic abundance of
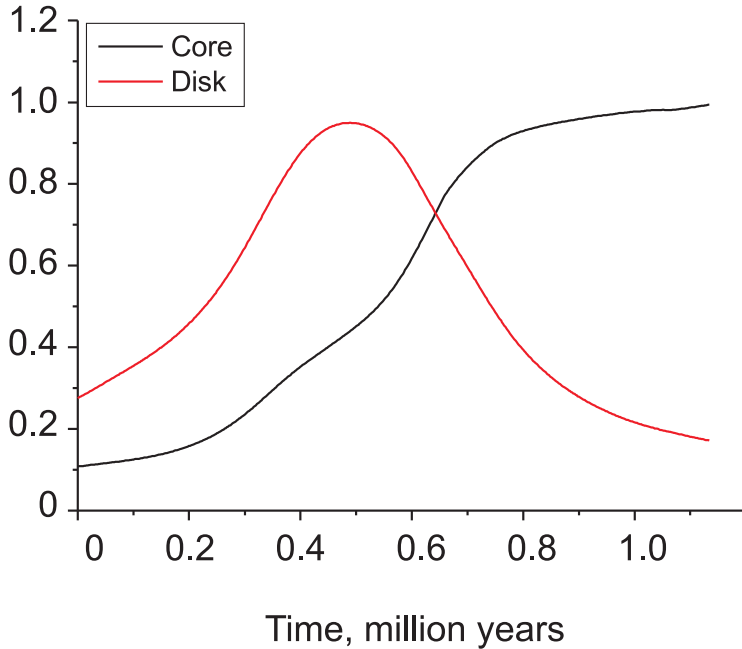
Figure 1. The mass of the disc and the protostar formed as a result of molecular cloud collapse. The unit is the mass of the Sun.

chemical elements [5] the main components of disc solids dust should be water and organic compounds from H, C, O, N with high molecular weights [6]. Such compounds can be easily synthesized on Mg, Si, O, Fe dust grains that work as catalysts in a medium with abundance of H and He [7]. That is why conglutination of multi-component organic compounds and non-organic bodies can be expected up to 1-10 meter in size. When the subdisc consists of such bodies with velocities greater than 10 km s^{-1} they collide less than once per orbital time.

The growth of planetesimals (i.e., bodies with a size in excess of a kilometer) may occur due to collisional accumulation, since their own gravitational field can attract smaller bodies and hold these to their surface [8]. The mechanism by which kilometer-sized planetesimals are formed from 'boulders' (or agglomerates, with sizes from $1 - 10$ m) has been the subject of intense interest and discussion, and has formed the basis of many studies. At this stage, the concentration of solids provides motion, with rare collisions at orbital time with velocities of tens kilometers per second. The meter-sized boulders are not enlarged during high-velocity collisions. Collisions of such boulders don't result in sticking irrespective of their composition. During collisions where the relative velocities exceed 1 m s^{-1}, inorganic compound solids larger than 10 cm are destroyed, rather than sticking together and becoming a larger, aggregate body. In addition, in circumstellar discs, the time taken for a meter-sized solid to fall to the central body is of the order of 100 years, due to gas drag. Thus, the growth of such solids in the disc may take only some tens of rotations [9]. If the growth goes slower, the protoplanetary

disc will lose a large proportion of its 'solid' matter, which is the material needed for the formation of Earth-group planets, and asteroids and comets.

4 What gravitational instabilities we need to form planetesimals

The formation of planetesimals can occur either in a massive circumstellar disc (age 0.1-1 million years, with the mass of the disc comparable to that of the central body) or in a medium-mass disc (age exceeding 1 million years, with the mass of the disc an order of magnitude less than the mass of the central body).

One possible way to rapidly assemble meter-sized boulders into a body of planetesimal size could be via gravitational instabilities triggered by the collective motion of the solids subdisc.

Gravitational instability in discs with a central body has been investigated since the 1950s [10]. It was found that to experience local Jeans instability, a disc with a central body needs lower dispersions in the velocities of solids [11], as well as lower gas temperatures [8] or higher-density matter (as compared with a motionless medium). Such conditions — which are close to those that trigger other instabilities in the disc [12] — may lead to the formation of rings, spirals, complex wave structures or individual clumps [13]. The formation of clumps in a rotating medium is hindered by gas heating, as well as the increasing velocity dispersion of solids produced by gravitational field perturbations in spiral and other wave structures. The non-linear behaviour of instabilities and the appearance of clumps (whose densities increase under self-gravitation) are therefore of interest. In any case, for discs to experience fragmentation, they should be quite dense and cold. Scenarios for the development of instabilities [14, 15] suggest that stable discs transform into unstable ones due to the sedimentation of solids on the equatorial plane. For instability development it was necessary to provide the surface density of the primary solids critical for this particle velocity dispersion. However, the formation of a dense primary solids subdisc is prevented by solids scattering, which is caused by turbulent gas flows resulting from hydrodynamic instability of the Kelvin-Helmholtz type [16]. This instability arises because both components of the two-phase subdisc located in the equatorial plane rotate at the Keplerian velocity, whereas the angular velocity of gas outside the plane is lower, due to the radial pressure gradient. A substantial difference in subdisc thickness (with respect to the gas and condensed phases) is not therefore expected.

On the other hand, a disc can reach its instability threshold not only by increasing its density, but also via a decrease in temperature. The main problem with implementing this mechanism in a medium-mass disc is that the lowering of the gas temperature in the disc is accompanied by a rapid formation of spiral structures, which do not transform into clumps. Spiral waves appear at higher temperatures in the medium-mass disc. In these spirals, the dispersion in the velocities of solids increases [17]. These structures — which result from the development of gravitational instability in the gas — scatter the subdisc of primary solids with sizes exceeding 1 m [18]. Rapid cooling, which typically occurs in a time comparable to the time taken for the disc rotation, was considered to be a necessary condition for clump formation in such a disc [19]. However, in the case of a medium-mass disc, such gas cooling conditions can hardly be expected to occur, due to the growing radiation from the star.

The mechanisms that facilitate the formation of planetesimals from large bodies have previously been studied for medium-mass discs. According to the computer simulation made by Rice et al. (2004, 2006) for a two-phase disc, meter-sized solid particles can concentrate in spiral arms for some time, due to gas dragging. Computational experiments by Youdin
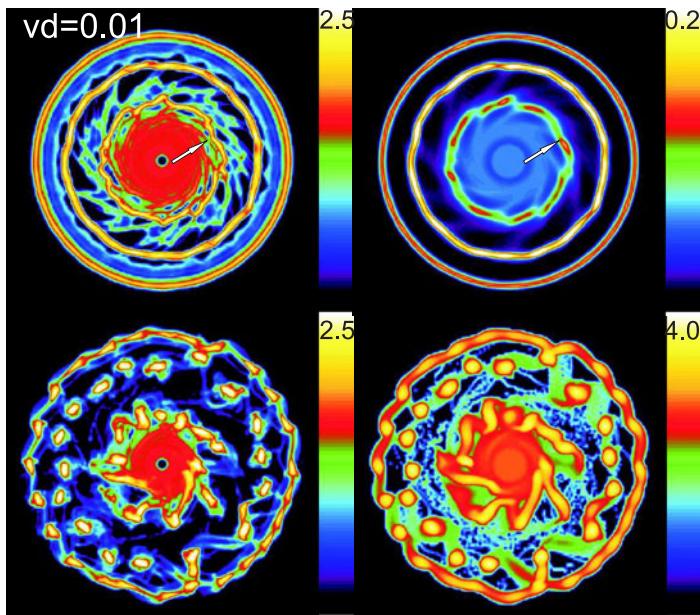
Figure 2. Surface density of solids in gas in linear (top right figure) or logarithm (other) scale at the time $T = 7$ (first line) and $T = 10$ (second line). $v_d = 0.01$. Formation and fragmentation of ring at small radii.

and Shu [20] demonstrated that a turbulent gas flow resulting from the difference in the angular velocities of the primary solids subdisc and the gas disc did not prevent gravitational instability which increases the concentration of solids. A condition for the development of instability is determined by the compression of the solid phase subdisc towards the star, in the equatorial plane. Such compression increases the ratio of the mass densities of the solid component and the gas by a factor of 2-10. The density of the medium in these regions starts to grow under the action of a self-gravitational field. Marov et al. [21] noted that the possibility of a local concentration of bodies should be considered; this local concentration may result from the differential rotation of the gas subdisc in large turbulent structures. According to Cuzzi et al.[16], such bodies will be represented by meter-sized boulders, since solids exceeding 1 m in size settle most efficiently on the equatorial plane. Meanwhile, smaller agglomerates are removed from this plane by a turbulent flow that results from the different angular velocities of the gas and solid-phase subdiscs.

Johansen et al.[22] investigated local gravitational collapses in medium of sub-meter-sized solids in the disc. Gas was not involved in such collapses. This mechanism was able to explain the growth of sub-meter-sized agglomerates into bodies with a size of 10 meters. These 10-meter-sized bodies experience rare but high-velocity collisions with each other during orbital time. In contrast to sub-meter-sized solids, drag forces do not cause such enlarged bodies to move in concert with gases.

Overall, the problem of planetesimal formation from primary solids, boulders and agglomerates in medium-mass quasi-stationary discs has not yet been convincingly solved. We
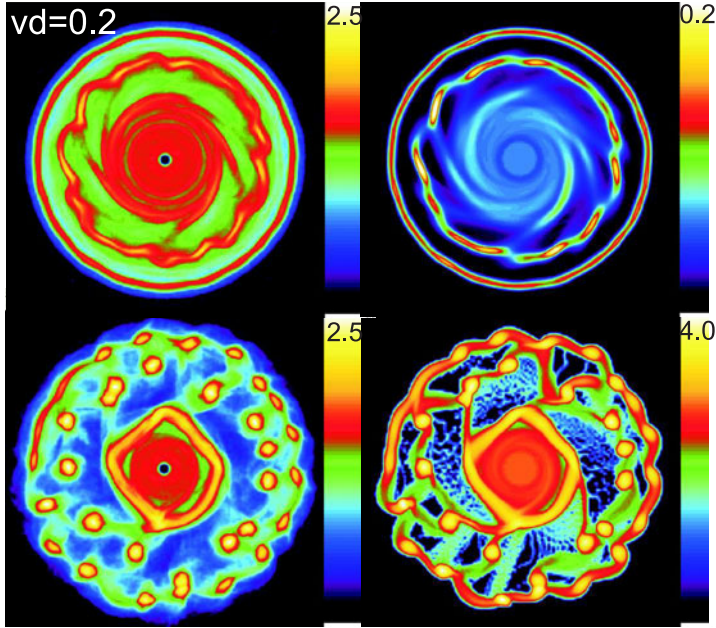
Figure 3. Surface density of solids in gas in linear (top right figure) or logarithm (other) scale at the time $T = 7$ (first line) and $T = 10$ (second line). $v_d = 0.2$.

therefore examined the possibility of planetesimal formation in the intermediate period between the existence of the massive accretion disc (see Fig.1, age of more than 0.1 million years, with the mass of the disc comparable to the mass of the central body) and the medium-mass disc (age of more than 1 million years, with the mass of the disc approximately 10 times smaller than the mass of the central body).

In [2] we demonstrated that the gravitational interaction of the two phases (gases and primary solids over a meter in size) affects the stability of the entire disc, and changes the conditions necessary for the formation of clumps in such a system by means of changing effective Jeans length for such systems.

For gas and collisionless medium the Jeans length can be estimated as $\Lambda_{par} = \dfrac{v_d^2}{G\sigma_{par}}$, $\Lambda_{gas} = \dfrac{c_{gas}^2}{G\sigma_{gas}}$. For hybrid system, when gas and solid move under the common gravitational field, it is a nonlinear combination of gas and solid bodies quantities: $\dfrac{1}{\Lambda} = \dfrac{1}{\Lambda_{par}} + \dfrac{1}{\Lambda_{gas}}$. Thus we can find also effective Toomre parameter for hybrid systems, that explains the influence of solids on global disc dynamics: $Q = \sqrt{\dfrac{\Lambda_{par}\Lambda_{gas}}{\Lambda_{gas} + \Lambda_{par}} \dfrac{\Omega^2}{G(\sigma_{gas} + \sigma_{par})}}$.

To capture that influence of solids on global structure formation we performed calculation of unstable massive disc dynamics, based on the mathematical model and the code described in [23]. We reproduced the dynamics of some turnovers of the disc with mass $M = 0.55M_0$

and radius $R = 2R_0 = 20$ au rotating round the central body with mass $M_c = 0.45M_0$. For quasi-$3D$-model specifying the ratio of surface densities and mass of entire disc, we determined the masses of gas and subdisc of primary solids, $M_{gas} = 0.52M_0$, $M_{par} = 0.03M_0$. Initial temperature was $T^*(r) \sim \sigma(r)$ with $T_0 = 0.01$ in the center, $\gamma^* = 5/3$.

Let us compare results of two calculations (see Fig.2 and Fig.3), where we varied parameter of solids only. In the first case we used velocity dispersion of solids $v_d = 0.01$ and in second case - $v_d = 0.2$ (in dimensionless parameters $c_s \sim 0.05$). By the same moment (half of the turnover of outer part of the disc) in first case 3 global ring was formed, when in second - only 2 at larger radii. Due to azimuthal instability these rings fall to individual clumps. Decreasing of Jeans length leads to increasing of the number of the clumps, that can be embryos of planets and large planetesimals.

5 Conclusion

We outlined the scenario of the planetary system formation, where large bodies are formed on the stage of massive discs. On this stage the whole of factors: chemical composition, physical conditions, chemical catalytic reactions, the disc self-gravitation, the increased ratio of solids to gas surface density, adiabatic gas cooling provides favorable conditions for gravitational instabilities development. Gravitational instabilities in multiphase medium can lead to planetesimal and planetary embryo formation.

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