Disk Self-Gravity Effects on the Time Evolution of the Solar Nebula

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We have studied the time evolution of a self-gravitating accretion disk around a low-mass protostar.

We found two major effects of the disk self-gravity. The one is the gravitational instability [1], and the other is making the vicous evolution time scale long. Furthermore, we found that the main source of these self-gravity effects is massive mass in the outer region, so the state of the inner region of the disk is very similar to the no self-gravity case.

We suppose the Solar Nebula was formed first as an accretion disk around the proto-Sun, in which mass transfer in the radial direction occurred for the Solar Nebula to evolve dynamically. Some researchers solved the steady state of this Solar Nebula [2][3], or calculated the time dependent solution of the disk [4]. All these works neglected the disk self-gravity. But when we consider the time evolution of the Solar system from the early phase where the mass of the proto-Sun is small, the disk self-gravity must not be neglected. So, in order to be more clear the formation processes of the Solar system, we have to calculate the time evolution of the proto-Sun and the Solar Nebula system from its early phase with taking into account the disk self-gravity. Particularly, our interests are pointed on the disk self-gravity effects that were neglected in previous works, so the main purpose of this work is to reveal the disk self-gravity effects on the evolution of the accretion disk.

We put the proto-Sun at the center of the system, whose mass is lower than the present Sun, and put the Solar Nebula as an accretion disk around the proto-Sun. We assume the system is axisymmetric. And we suppose that the disk is geometrically thin, otically thick, and in the disk the motion of the gas is turbulent, so turbulent viscosity forces the mass and angular-momentum of the disk transfer in the radial direction. The main source of the turbulence is supposed to be the convective instability between the midplane and the surface of the disk. And we assume that the viscosity representation is given by the α-model as follows, $\nu_{conv} = \alpha c_s h$, where ν_{conv} is the viscosity coefficient, α is a non-dimensional parameter, c_s is the sound speed, and h is the half-thickness of the disk. The disk region that we are interested in is from 0.5 AU to 50 AU. We suppose that the mass from the interstellar cloud is accreted on the far distant outer region of the disk, so we neglect the mass accretion onto the disk surface. The mass transfering through the inner disk boundary is supposed to accrete onto the central proto-Sun; hence the proto-Sun grows.

We calculated various cases of parameters. One typical case is following one. The initial state is that the proto-Sun's mass $M_c = 0.5 M_\odot$ (where $M_\odot$ is the present solar mass) and the disk mass $M_d(0.5\text{AU} < r < 50\text{AU}) = 0.156 M_\odot$. The mass accretion rate $\dot{M} = 10^{-6} M_\odot/\text{yr}$, and $\alpha = 10^{-2}$. The surface density distribution of this case after 10^6 years is shown in *figure 1*. We calculated time evolution in three manners; (1)taking into account the disk self-gravity, (2)no disk self-gravity, (3)taking into account the disk self-gravity and furthermore the turbulent viscosity not only by the convective instability, ν_{conv}, but also by the gravitational instability, ν_g ($\nu_g = \lambda^2\omega$; λ is the most unstable wave length and ω is its growth rate). In the calculation manners (1) and (2), we suppose that the gravitational instability does not give any effects to the state of the system and so the value of α is kept constant 10^{-2}, and in the manner (3), we assume that the gravitational instability causes the turbulent motion in the disk and this turbulence contributes to viscosity.

In the *figure 1*, the line marked Σ_{crit} indicates the critical value of the surface density to the gravitational instability for the no self-gravity calculation's result, and the curves that are marked (1),(2),(3), are corespondent to the calculation manner's number, respectively. The *figure 1* shows that the disk self-gravity which does not cause turbulence or devide the disk, makes the disk evolution time scale long. And it shows that the surface density distribution of the calculation manner (3) is very similar to the manner (2) in the relevent inner region. This fact says that the main source of the disk self-gravity effects is the mass in the outer region of the disk. Now we can conclude that the surface density distribution in the case that the gravitational instability causes turbulence in the disk, is got by the distribution of the no self-gravity case in the relevent inner region and by the critical surface density in the relevent outer region.

Furthermore, from the another cases of calculation, we found that the surface density distributions in the *figure 1* are almost independent of the initial states, and we also found that when the central protostar's mass M_c is about one solar mass, the disk mass $M_d(0.5\text{AU} < r < 50\text{AU})$ is about 20 - 30 percent of M_c.

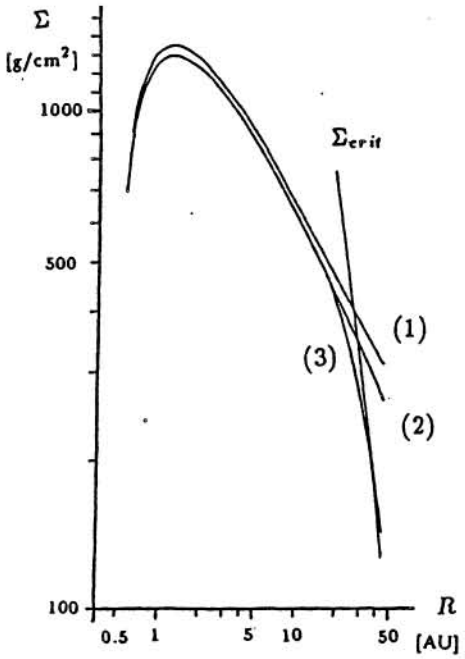

Figure 1. The distribution of the surface density after 10^6 years with mass accretion rate $\dot{M} = 10^{-6} M_\odot/\text{yr}$ and $\alpha = 10^{-2}$. The curve marked (1) indicates the result of the calculation manner (1), namely taking into account the disk self-gravity case. The curve marked (2) represents no self-gravity case, and curve (3) represents the case that taking into account the disk self-gravity and the turbulent viscosity by convective instability as well as gravitational instability. The line marked Σ_{crit} indicates the critical value of the surface density to the gravitational instability for the no self-gravity calculation's result. A very interesting fact is that the surface density distribution of the curve(2) and curve(3) are very similar in the inner region, and also Σ_{crit} and curve(3) are very similar in the outer region.

Table 1.
Mass of the protostar M_c and the disk M_d

	M_c	M_d	M_d/M_c
(1)	1.1738	0.3418	0.291
(2)	1.2097	0.3060	0.253
(3)	1.2828	0.2328	0.181

(in $M_\odot$ unit)

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