Formation and evolution of the protoplanetary disks

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Abstract

Since planetary systems are formed in the protoplanetary disks, the formation process of the planets depends on the protoplanetary disks. To reveal the formation process of the planets, investigation of the structures of protoplanetary disks is important. In this thesis, we investigate the formation and evolution process of the protoplanetary disks.

The protoplanetary disks are formed with the protostars. The formation of the protostars and protoplanetary disks starts from the gravitational collapse of the molecular cloud cores. Since the cloud cores have angular momentum, the gas cannot accrete onto the protostars directly and the gas forms the protoplanetary disks around the protostars. Numerical simulations suggest that the protoplanetary disks are massive in the early evolution stage. In the massive disk, spiral arms are formed due to the gravitational instability. The angular momentum of the protoplanetary disks is redistributed due to the gravitational torque of the spiral arms. The gas that loses the angular momentum accretes onto the protostars through the disks.

Since it is difficult to calculate the whole process of the protoplanetary disks with three-dimensional simulations, we develop a simplified one-dimensional accretion disk model that takes into account the infall of gas from the cloud core onto the disk and the angular momentum transfer in the disk with an effective viscosity. We formulate the effective viscosity as a function of the Toomre's Q parameter that measures the local gravitational stability of the rotating thin disk. We use a function for viscosity that changes sensitively with Q when the disk is gravitationally unstable. We find a strong self-regulation mechanism in the disk evolution. During the formation stage of protoplanetary disks, the evolution of the surface density does not depend on the other details of the modeling of effective viscosity, such as the prefactor of the viscosity coefficient. To verify our model, we compare the time evolution of the disk calculated with our formulation with that of three-dimensional hydrodynamical simulations. The structures of the resultant disks from the one-dimensional accretion disk model agree well with those of the three-dimensional simulations. Our model is a useful tool for the further modeling of chemistry, radiative transfer, and planet formation in protoplanetary disks.

In the case where the protoplanetary disks are massive enough, the fragmentation occurs due to the gravitational collapse. The fragmentation of the protoplanetary disks is candidate of the formation process of the binary systems, brown dwarfs and gas giant planets. In the gravitationally unstable

disk, the spiral arms transfer the mass of the disks and increase the temperature due to the shock heating. As a result, $Q \sim 1$ is sustained in the self-gravitating disks where the spiral arms are formed. The previous works have proposed that the condition for the fragmentation in such disks is that the cooling timescale is comparable to the dynamical timescale. However, this condition conflicts with the results of the numerical simulations on the formation of protoplanetary disks, which suggest the fragmentation occurs even in the adiabatic disks. To clarify the condition for the fragmentation of the self-gravitating disks, we perform the two-dimensional numerical simulations that take into account the effect of the irradiation of the central star and radiation cooling of the disks, and investigate the structure of the spiral arms. We find that the Toomre's Q parameter in the spiral arms is important for the fragmentation. The condition for the fragmentation is that the $Q \lesssim 0.6$ is satisfied in the spiral arm in the length two times as long as width of the spiral arms. The initial surface density required for the fragmentation increases with increasing opacity. In the case where the typical Q value of the disks is larger than ~ 2, the disks are not fragment independently of the opacity, and in the case the typical Q decreases to about unity, disks are fragment even when the disks is adiabatic.

Even in the case where the protoplanetary disks are gravitationally stable, the friction between gas and dust can make the disks unstable. We perform the local linear stability analysis of self-gravitating gas and dust to investigate the instability. If we ignore the dynamical feedback from dust grains in the gas equation of motion, the instability reduces to the so-called "secular gravitational instability", which was investigated previously to be an instability of dust in a fixed background gas flow. We solve the equations of motion for both gas and dust consistently and find that long-wavelength perturbations are stable, in contrast to the secular gravitational instability in the simplified treatment. This may indicate that we should not neglect small terms in the equation of motion if the growth rate is small. In the case where the dust-to-gas ratio is enhanced and turbulence is weak, the instability grows, even in gravitationally stable disks, on a timescale of order 10^{4-5} yr at a radius of order 100 AU. Thus the instability is expected to form ring structures in protoplanetary disks in such a timescale. The width of the ring formed at a radius of 100 AU is a few tens of AU. Therefore, the instability is a candidate for the formation mechanism of observed ring-like structures in disks.