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Dust Particle Settling in Protoplanetary Disks around Young Stars in Binary Systems

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Abstract. We calculate the SEDs of young stars accompanied by protoplanetary disks, taking into account the effect of the settling of dust particles. Observed disk candidates contain significant number of binary or multiple systems. We compare our results with observed data and obtain many excellent fittings. From the results, it is found that in close binary systems the disk masses are relatively low and dust particles is hard to settle as compared with the cases of disks in wide binaries or around isolated stars. This is attributable to gravitational perturbation from the companion stars, which will disturb formation of planetary systems in close binary systems.

1. Motivation

Recent mm/sub-mm and IR observations provide us with much evidence of disk formation around various kinds of young stars. The most remarkable result is that many disk candidates have been detected around young stars in binary or multiple systems (e.g., Osterloh & Beckwith 1995). It is well known that the majority of stars are in binary or multiple systems. It becomes more and more important to consider the evolution of disks in binary systems. The above observations stimulated us to investigate the mechanism of the disk formation and settling of dust particles in the star-disk system in binary systems. In this paper we calculate SEDs of young stars with disks in binaries as well as those of single isolated stars theoretically and compare the results with observed fluxes. Especially, for passive disks which have no intrinsic heat sources, we can easily calculate SEDs using the radial temperature distribution in thermal equilibrium. The shape of SEDs differs with disk flaring or settling of dust particles and, hence, we can infer the internal structure of the disk. We obtained many excellent fits with observed fluxes, which support the validity of our model. Our work might then shed light on some unresolved issues of disks around young binaries or multiples as follows: internal structure of disks, difference between close and wide binaries, possibility of planetary system formation, and so on.

2. Method

In order to derive the SED of a star-disk system, we first consider the temperature distribution in radial direction of the disk. The disk is presumed to be vertically isothermal. The most plausible method to determine the disk temperature is to solve the equation of the thermal equilibrium between heating by the stellar radiation and cooling by thermal emission. In addition to the standard formula (Kusaka, Nakano & Hayashi 1970), we also consider the effect of particle settling (Miyake & Nakagawa 1995) and optically thin outer part of the disk through the optical depth τ for thermal radiation (Chiang & Goldreich 1997):

$$(1-e^{-2\tau})\sigma T(r)^4 = \frac{L_*}{8\pi r^2}\left[\frac{4}{3\pi}\left(\frac{R_*}{r}\right)+\left(\frac{fH}{r}\right)\left(\frac{d\ln fH}{d\ln r}-1\right)\right], \qquad (1)$$

where L_* and R_* are the luminosity and the radius of the central star, respectively. The parameter f, varying from 0 to 1, represents a correction factor for the difference between the scale height of the disk H and that of the surface absorbing stellar radiation fH. The parameter $f = 1$ corresponds to a condition where dust particles are well mixed with gas and the particles have not started to settle. As the dust particles settle toward the midplane of the disk, the height of the absorbing surface becomes lower and, hence, the value of f-factor decreases toward zero. Intermediate values of f between 1 and 0 represent the corresponding transient stages of particle settling. The parameter $f = 0$ corresponds to a condition where dust particles have completely settled to the midplane. Thus, the parameter f represents the settling degree of dust particles in the disk.

Next, we obtain the SEDs (or the luminosity densities) of model star-disk systems by substituting the temperature distribution determined by Eq. (1) into the following formula (2). The luminosity density L_ν viewed at the angle θ is given by

$$L_\nu = 4\pi\cos\theta\int_{R_0}^{R_d}\nu B_\nu(T)(1-e^{-\tau_\nu})2\pi r dr + L_{\nu *}, \qquad (2)$$

where B_ν is the Planck function, $L_{\nu *}$ is the stellar component of L_ν, R_0 and R_d are the inner and outer radii of the disk, respectively; and the slant optical depth τ_ν is given by

$$\tau_\nu(r) = \kappa_\nu\Sigma(r)/\cos\theta, \qquad (3)$$

where κ_ν is the absorption opacity for dust particles (Miyake & Nakagawa 1993) and $\Sigma(r)$ is the surface mass density of the disk. Dust species are assumed to be only silicate for the regions where $T > 160$ K and silicate plus H_2O ice for the regions where $T \leq 160$ K.

3. Results

We at first describe the results of numerical calculations of Eq. (1), adopting the typical values for T Tauri stars in the Taurus-Auriga cloud complex: $T_* = 4000$ K, $L_* = 1\ L_\odot$, and $M_* = 1\ M_\odot$. The disks are assumed to extend from the surface of the central star to $r = 100$ AU. It is found the power-law index of temperature distribution with respect to r ($T \propto r^{-q}$) is almost $q = 3/4$ for

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$r < 1$ AU even for $f = 1$ and decreases toward $q = 1/2$ for larger r up to 10 AU. The index $q = 3/4$ for small r is expected for thin disks heated by the central star with finite dimension. The radial distance where the index q changes increases for smaller f-values. In the region where $r \geq 10$ AU, the temperature T hardly decreases with increasing r (for $f = 0$) or increases instead (for $f = 1$). It suggests that dust particles emit thermal radiation less efficiently in the outer region of the disk due to the tenuous density. We also calculated the SEDs of passive disks for various f-factors. For $f = 1$, we found a considerable enhancement in the SED around $\nu \simeq 10^{12.5}$ Hz (i.e., $\lambda \simeq 100\ \mu$m) due to dust opacity (Sato & Nakagawa, 1999).

4. Concluding Remarks

From the above results we can infer the possibility of planetary system formation in binary systems. It seems that disks can hardly be formed and, even if disks are formed, their masses will be relatively low in close binary systems (Osterloh & Beckwith 1995). We obtained excellent fits between our SEDs and observed fluxes from many young stars with disks. Based on our results of SED fittings of binary systems, we plot settling degree of dust particles (f-factor) against binary separation in each system. From the result it is found that particle settling occurs more hardly in close binaries compared with wide binaries. It is a natural consequence, because gravitational force of the companions will perturb the orbits of disk material in close binaries, that is, the companions with small separations tend to prevent planetary systems from being formed. We also investigated effects of particle settling on SEDs in single-star and disk systems and compared those results with the above cases in binaries; then we found that in wide binaries particle settling and subsequent planetary system formation are considered to occur just as in the disks around single stars.

References

Miyake, K., & Nakagawa, Y. 1995, ApJ, 441, 361
Kusaka, T., Nakano, T., & Hayashi, C. 1970, Prog. Theor. Phys., 44, 1580
Chiang, E. I., & Goldreich, P. 1997, ApJ, 490, 368
Miyake, K., & Nakagawa, Y. 1993, ICARUS, 106, 20
Strom, K. M. et al. 1989, AJ, 97, 1451
Osterloh, M., & Beckwith, S. V. W. 1995, ApJ, 439, 288
Sato, Y., & Nakagawa, Y. 1999, Proc. of Star Formation 1999, 235