Crystallization of Dust Particles in Protoplanetary Disks by Shock Wave Heating

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Astronomical observations have revealed that some comets and some protoplanetary disks around T Tauri stars have crystalline silicate dust particles. On the contrary, it is known that dust particles in interstellar clouds are amorphous. Thus, it is considered that interstellar amorphous dust particles incorporated to the protoplanetary disk or the solar nebula were heated and crystallized by some heating events before being incorporated to comets and/or planetesimals. It seems important to reveal the annealing process of dust particles in the disk when we address the formation of comets, planetesimals, and eventually the planetary system.

In this study, we examined the crystallization process of dust particles in the protoplanetary disk or the solar nebula by the shock-wave heating. Dust particles in the gas medium are heated by the shock-wave heating mechanism, if appropriate shock waves are present in the disk. In the first step of this study, we have carried out numerical simulations of the shock-wave heating, and obtained conditions of shock waves (the pre-shock gas density and the shock velocity) that are appropriate for the silicate dust crystallization. When the maximum temperature of dust particles is as high as 1100 K or more, those dust particles are crystallized within about a few seconds. In general, when the pre-shock gas density is high and/or the shock velocity is fast, the maximum dust temperature becomes high. On the other hand, if the maximum dust temperature is too high, dust particles are thought to evaporate away completely. These factors would lead to appropriate conditions of shock waves for crystallization. In our numerical simulations, we used the Silicate Evolution Index given by Hallenbeck et al. (2000) to determine if the dust particle is crystallized or not.

In the second step of this study, we discussed which shock generation mechanism is appropriate for the crystallization of the dust particles. Following are possibilities that may generate shock waves in the protoplanetary disk: (1) accretion shock at the surface of the disk, (2) spiral density wave in the disk, (3) bow shocks in front of planetesimals, (4) shock waves induced by large planets, and (5) shock waves induced by X-ray flares of the central star. We examined if shock waves generated by those mechanisms can crystallize the dust particles or not. According to the results, shock waves generated by (1)~(4) can crystallize dust particles if dust particles are within about 10 - 20 AU, though there are some uncertainties depending on the protoplanetary disk model. On the other hand, shock waves generated by (5) can crystallize dust particles within at least about a few AU. But it is still unclear how far the shock waves appropriate for dust crystallization can be generated in this mechanism, because there are no numerical simulations on the generation of shock waves further than about 3 AU.

The ratio of the crystalline dust particles to the total dust particles has not been estimated in the shock-wave heating model, which is the future work. It is considered that, in general, dust particles in the protoplanetary disk would move along the radial direction. Then, it is not clear if crystalline dust particles are heated and crystallized at the place where they are observed now, or if crystalline dust particles were transferred from crystallization region to the place where they are seen today. This issue also should be addressed in the future.