Shock Waves in Protoplanetary Disk Generated by Magnetic Bubbles of X-Ray Flares II: Crystallization of Dust Particles and Chondrule Formation.

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Introduction: Astronomical observations show that crystalline silicates are present in circumstellar disks around T Tauri stars and Herbig Ae/Be stars [e.g., 1, 2]. Also, crystalline silicates have been found in comets [e.g., 3]. Since almost all the dust particles in the interstellar medium are amorphous [4], the crystalline silicates have to be crystallized in the protoplanetary disk. One possibility to crystallize dust particles is to anneal them in the disk. On the other hand, chondrules in chondrite meteorites are formed by heating and melting in the solar nebula. Thus, it is expected that some sort of heating process may anneal dust particles and/or may form chondrules be present in the protoplanetary disk. According to previous work, when appropriate shock waves are present in the disk, dust particles are heated by the shock-wave heating mechanism [5-8]. Here, we show that shock waves appropriate for the crystallization or chondrule formation are generated in the disk by X-ray flares associated with young stars [9].

Shock-Wave Heating for Dust Particles: Shock-wave heating mechanism for dust particles have been studied in detail [e.g., 5-8]. Shock waves generally lead to the relative velocity between the dust particles and the gas. The relative velocity causes the gas frictional heating on the dust particle and heats them. Principal parameters of the shock-wave heating mechanism are the shock velocity and the pre-shock gas number density [6]. A detailed model of the shock-wave heating mechanism for dust particles revealed shock parameters appropriate for chondrule formation [6]. And similar simulations can provide shock parameter for dust annealing. Crystallization of dust particles is evaluated by using the silicate evolution index proposed by [9]. These results are summarized in Figures 1 and 2: Colored regions represent appropriate shock conditions for chondrule formation (Fig. 1) and crystallization (Fig. 2), respectively.

Shock Waves Generated by X-Ray Flares: Recent MHD numerical simulations suggest that X-ray flares that are associated with young stars can generate shock waves in the protoplanetary disks [10]. Generated shock waves have a wide range of velocities and the pre-shock gas number densities. They depend on the magnetic field strength at the vicinity of the central star, the gas density and the temperature of the disk, and so forth.

Thermal Processing of Dust Particles: Now the question is whether or not the appropriate shock waves for annealing and chondrule formation are generated in the disk by X-ray flares. Using two-dimensional MHD simulations [10] and one-dimensional plane-parallel radiation-hydrodynamics simulations [11], we have examined the shock velocity and the pre-shock gas density. It should be noted that the generated shock waves depend on many factors, such as the strength of the magnetic field in the vicinity of the central star, the density and the temperature of the disk, and so on.

Chondrule Formation: Figure 1 implies that chondrule formation needs more energy than annealing small dust particles. But according to the MHD simulations [10], it is shown that very strong shock waves can be generated in the disk in some cases: for example, when the total energy released from the X-ray flare is $10^{36}$ erg, which is close to the maximum value observed in T Tauri stars, shock waves of 90 km s$^{-1}$, 26 km s$^{-1}$, and 15 km s$^{-1}$ in propagation speed are generated at $R = 2$, 2.5, and 3 AU, and $Z = 0.9$ h, respectively, where $h$ is the scale height of the disk. And the pre-shock gas number density of those shock waves are $10^{13.3}$ cm$^{-3}$, $10^{13.0}$ cm$^{-3}$, and $10^{12.8}$ cm$^{-3}$, respectively. By comparing these values with Fig. 1, we can find that dust particles in certain places in the disk can be heated enough and chondrules can be formed by those shock waves.

Crystallization of Small Dust Particles: To see the propagation of shock waves at an outer region of the disk, where it is hard to carry out two-dimesional MHD simulations, we have carried out one-dimensional radiation-hydrodynamics calculations assuming the input momentum at the upper boundary of the disk. When we assume that the gas density and the velocity of the wind (expanding bubble generated by X-ray flare) are $\rho_w = 10^{12}$ g cm$^{-3}$ ($R/3$ AU)$^{-2}$ and $V_w = 100$ km/s, we obtain the shock velocities and the pre-shock gas number densities at $R = 3$ AU as 30 km s$^{-1}$ and $5 \times 10^{10}$ cm$^{-3}$ at $Z = 2$ h, 12 km s$^{-1}$ and $1.2 \times 10^{10}$ cm$^{-3}$ at $Z = 1.8$ h, and 5 km s$^{-1}$ and $2.3 \times 10^{10}$ cm$^{-3}$ at $Z = 1.6$ h, respectively. The velocity of the shock wave decreases as the shock propagates downwardly in the disk, while the pre-shock gas
density increases. Comparing the results with Figure 2, we can see that in the 3 AU region dust particles in $Z = 1.6 - 1.8 h$ region are annealed by the shock wave. Similarly, propagation of shock waves at 10 AU region is calculated and results are summarized in Figure 3. In this region, again appropriate shock waves for crystallization can be generated: 100 km s$^{-1}$ and $2 \times 10^7$ cm$^{-3}$ at $Z = 2 h$, 60 km s$^{-1}$ and $7 \times 10^7$ cm$^{-3}$ at $Z = 1.8 h$, and 20 km s$^{-1}$ and $1.3 \times 10^8$ cm$^{-3}$ at $Z = 1.6 h$, respectively. We can find that dust particles in $Z = 1.6 - 1.7 h$ region can be crystallized by those shock waves. Our preliminary estimates imply that dust particles within about 80 AU from the central star and in the upper region of the disk can be annealed by shock waves induced by X-ray flares.

Discussion: It seems natural that small dust particles, 0.1 $\mu$m in radius, are present in the upper region of the disk, such as $Z \sim 2 h$, because of the gas motion in the disk. Thus, we can naturally expect that small dust particles in the disk are crystallized due to shock waves generated by X-ray flares. On the contrary, it is not obvious that chondrule precursor dust particles, 0.1 mm or more in radius, are present in the $Z \sim 1 h$ region. It may be possible to lift them up to as high as 2 $h$, according to an analysis [12]. However, further studies for the large dust particle distribution along the vertical direction are clearly needed. On the other hand, we have to also clarify until where the shock waves can reach in the disk. These issues should be addressed in the future.

Summary: We have carried out two-dimensional MHD simulations and one-dimensional plane-parallel radiation-hydrodynamics simulations to examine whether or not shock waves appropriate for the crystallization and chondrule formation are generated in the disk by X-ray flares. We have found that some shock waves that can crystallize small dust particles are generated. Also, we found that some shock waves can heat dust particles enough and form chondrules.