Chondrule Forming Shock Waves Induced by X-Ray Flares

Taishi Nakamoto[1]; Mitsuru Hayashi[2]; Noriko, T. Kita[3]; Shogo Tachibana[4]

[1] CCP, Univ Tsukuba; [2] NAO; [3] GSJ, AIST; [4] Earth and Planet. Sci., Univ. of Tokyo

Chondrules are considered to have been formed by some flash heating events in the early solar nebula. Though the specific heating mechanism has not yet been understood clearly, the shock-wave heating is considered to be the most plausible mechanism to explain the various properties of chondrules. However, the source of shock waves and the place of the shocks in the nebula are not yet revealed.

Here, we propose a new model: shock waves in the upper solar nebula induced by X-ray flare winds associated with the young Sun. X-ray flares, common among T Tauri stars, emit plasma gas, which cools to be a strong neutral gas wind. The energy, the dimension, and the frequency of X-ray flares associated with T Tauri stars are much larger than those of the current Sun. For example, typical luminosity in the X-ray wavelength region is about two orders of magnitude higher than the current solar flare. Because of the enormous amount of energy released by the X-ray flares, the flares should have significant effects on the dynamics and energetics of a disk around the star. Observations of X-ray flares around young T Tauri stars indicate that their activity decreases with a time scale of the order or 10^6 yr, which is similar to the range of chondrule ages, i.e., from about 1 Myr to 3 Myr after CAI formation (Kita et al. 2000, Mostefaoui et al. 2002). In this work, we estimate the influence of the X-ray flares to the nebula and evaluate the possibility of chondrule-forming shock waves in the nebula. We focus on shock waves in the upper solar nebula.

We can expect that a shock wave should occur at a place where the ram pressure of the impacting wind becomes the same with the static gas pressure of the nebula gas. The ram pressure can be estimated by P_ram(R) = M_dot V cos _ / (__R^2), where R is the distance from the Sun, M_dot is the mass flux of the wind, V is the wind velocity, _ is the impact angle to the nebula surface, and _ is the solid angle of the expanding wind. According to numerical simulations (Hayashi et al. 1996), the mass flux of the outflow is estimated to be M_dot = 10^-8 (V/ 170 km s^-1) M_sun yr^-1. We assume the solid angle _ of the expanding wind is _i/2, since the wind is not spherically symmetric with respect to the star. And we assume cos _ = 0.01. As for the nebula gas pressure P_neb(R, Z), we evaluate it using the minimum mass solar nebula model.

By balancing two pressures, P_ram(R) = P_neb(R, Z), we can estimate the height where shock wave is expected to be present as a function of R: Z_shock/h(R) = [9.47 - 1.25 ln(R / 1 AU)]^{1/2}, where h(R) is the scale height at R. We can see that Z_shock/h is in a rather narrow range from 2.78 (R = 4 AU) to 2.93 (R = 2 AU). Nebula gas densities at those heights before being smashed by winds are 1.4 x10^-14 g cm^-3 (R = 4 AU) and 3.9 x10^-14 g cm^-3 (R = 2 AU), respectively. Although those gas densities are much smaller than those in the nebular mid-plane, in reality, it is expected that the nebula gas is compressed by the shock and the nebula density is enhanced to an extent, though the degree of enhancement is not known precisely.

According to numerical simulations of shock-wave heating chondrule formation (Iida et al. 2001, Miura & Nakamoto 2004), 0.1-mm sized dust particles can be heated enough to melt and form chondrules, when the preshock gas density is of the order of 10^-14 - 10^-13 g cm^-3 and the shock velocity is several tens km s^-1. Our MHD numerical simulations have shown that winds induced by X-ray flares can generate shock waves with those properties in the upper solar nebula.

Therefore, it was found that X-ray flares can generate shock waves that are suitable for chondrule formation in the upper solar nebula. This model, "winds induced by X-ray flares + shock-wave heating of dust particles," is a new model we propose here for chondrule formation.