GENERATION OF CHONDRULE FORMING SHOCK WAVES IN SOLAR NEBULA BY X-RAY FLARES. T. Nakamoto[1], M. R. Hayashi[2], N. T. Kita[3], and S. Tachibana[4]; [1]Center for Computational Sciences, Univ. of Tsukuba (Tsukuba, Ibaraki 305-8577, Japan; nakamoto@ccs.tsukuba.ac.jp), [2]National Astronomical Observatory Japan (Mitaka 181-8588, Japan), [3]Dept. of Geology and Geophysics, Univ. of Wisconsin (Madison, Wisconsin, WI 53706, USA), [4]Dept. of Earth and Planetary Science, Univ. of Tokyo (Tokyo 113-0033, Japan).

Introduction: Chondrules are considered to have formed through 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 one of the most plausible models to explain the various properties of chondrules; peak temperatures, stability of melt droplets, the size range, and heating rates [e.g., 1-7]. However, source of shock waves is still under debate. Proposed models include bow shocks in front of fast moving planetesimals [8], accretion shocks at the surface of nebula [9], and spiral density waves induced by the disk self-gravity [10], though every model has some drawbacks.

Here, we report that chondrule forming shock waves can be generated in the upper region of the solar nebula by X-ray flares associated with the young Sun. X-ray flares, common among T Tauri stars [11], 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. Typical luminosity in the X-ray wavelength region is about two orders of magnitude higher than the current solar flare [11]. Since the energy released by the X-ray flares is so large, it is naturally expected that the flares have some effects on the dynamics and energetics of a protoplanetary disk around the star. Observations of X-ray flares around young T Tauri stars indicate that their activity lasts of the order of 10^6 to 10^7 yr [11], which is consistent with the range of chondrule formation ages [e.g., 12-14].

In this work, we numerically simulate the X-ray flares and expanding magnetic bubbles with the disk, and examine whether or not shock waves which can form chondrules are generated in the nebula. Preliminary results were reported last year [15].

MHD Simulations: We have carried out 2-D Magneto Hydrodynamics (MHD) simulations of X-ray flares around a central star and expanding magnetic bubbles/winds with a disk. The minimum mass solar nebula model [16] is employed as the disk model. Outer boundary of the computation domain is 3 AU from the central star, and the number of grid points in the computational domain is 1300x1300. Details of numerical procedure are described in [17].

The temperature distribution in a global view at t = 6.665 days after the X-ray flare event is displayed in Figure 1. 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. The expanding bubble is clearly shown. Main part of the bubble goes upward along the rotational axis, and which seems to become the jet or outflow. On the other hand, it can be seen that a certain fraction of the bubble goes toward the disk and interacts with the disk.

In figure 2, the density distribution in a 1 AU region at t = 7.046 days is displayed. We can clearly see that the density jump, i.e., the shock front, is generated in the upper region of the disk. We measured the propagation speed of the front, which turned out to be about 100 km/s.

Comparing results of out current study with [3], where suitable shock conditions for chondrule formation were investigated, it seems that the shock waves at 1AU seen in Figure 2 is so strong to heat the dust particles that dust particles are expected to evaporate away completely.

We have carried out several simulations with other parameters, and found that (a) shock waves that are appropriate for the chondrule formation are generated in the upper region of the disk, and (b) the propagation speed of the shock front depends, at least, on the strength of the magnetic field and the gas pressure. Comparing these results with [3], we can see that dust particles in the upper region of the disk can be heated enough and can form chondrules by the shock wave heating mechanism. For example, chondrule forming shock waves, whose velocity is about 30 km/s and the pre-shock gas density is about 10^{12} cm^{-3}, were generated with weaker magnetic fields than that of the Figure 1 case.

Discussions:

Presence of Chondrule Precursor Particles in Upper Solar Nebula: In the absence of turbulence, the chondrule precursor particles of 0.1 mm radii may not be present in the upper region of the solar nebula, because the sedimentation time scale of dust particles is of the order of 10^4 yr [18] (shorter than the age of chondrules). However, turbulence in the nebula may lift precursor particles in the upper region for longer time. For example, using a turbulent nebula model, it was shown that 0.1-mm sized dust particles could be present at $Z = 3\ h$ (h is the gas scale height of the disk) [19].

Dust to Gas Mass Ratio in front of Shock Waves: An analysis for the collisional destruction among dust particles in shock waves [20] showed that the dust/gas mass ratio before entering the shock wave should be of the order of or less than 0.01, otherwise, the chondrule size distribution in ordinary chondrites cannot be reproduced. This inferred dust/gas mass ratio is consistent with the current model, because the dust concentration in the upper solar nebula is expected to be small.

A Variety of Chondrule Ages: The difference of ages among chondrules in the same meteorites is at least 1 Myr [e.g., 12, 13]. This implies that each heating event influences only a limited portion of chondrules at a time, otherwise, older chondrules should be reheated and their age difference should be much smaller. Our model may meet this requirement. The heating events take place only in the upper part of the nebula, while most of the dust particles including previously formed chondrules stay in the lower part of the nebula.

Chemical and Isotopic Properties of Chondrules: The evidence of a large degree of isotopic fractionations has not been found in chondrules [e.g., 21]. It should be investigated whether or not the proposed heating mechanism can explain such properties of natural chondrules in future work.

References: [1] Jones R. H. et al. (2000) in *Protostars and Planets IV*, 927-962. [2] Boss A. (1996) in *Chondrules and the Protoplanetary Disk*, 257-263. [3] Iida A. et al. (2001) *Icarus 153*, 430-450. [4] Miura H. et al. (2002) *Icarus 160*, 258-270. [5] Susa H. and Nakamoto T. (2002) *ApJ 564*, L57-60. [6] Miura H. and Nakamoto T. (2005) *Icarus*, in press. [7] Miura H. and Nakamoto T. (2005) *Antarctic Meteorite Research*, in press. [8] Weidenschilling S. J. F. et al. (1998) *Science 279*, 681-684. [9] Tanaka K. K. et al. (1998) *Icarus 134*, 137-154. [10] Desch S. J. and Connolly H. C. Jr. (2002) *MAPS 37*, 183-207. [11] Feigelson E. D. et al. (2002) *ApJ 572*, 335-349. [12] Kita N. T. et al. (2000) *GCA*, *64*, 3913. [13] Mostefaoui S. et al. (2002) *MAPS 37*, 421-438. [14] Nakamoto T. et al. (2003), *LPS XXXIV* abstract #1323. [15] Nakamoto T et al. (2004) *LPS XXXV* abstract #1821. [16] Hayashi C. et al. (1985) in *Protostars and Planets II*, 1100-1153. [17] Hayashi M. R. et al. (1996) *ApJL 468*, L37-L40. [18] Nakagawa Y. et al. (1981) *Icarus 45*, 517-528. [19] Takeuchi T. and Lin D.N.C. (2002) *ApJ 581*, 1344-1355. [20] Nakamoto T. and Miura H. (2004) *LPS XXXV* abstract #1847. [21] Alexander C. M. O'D et al. (2000) *MAPS 35*, 859-868.

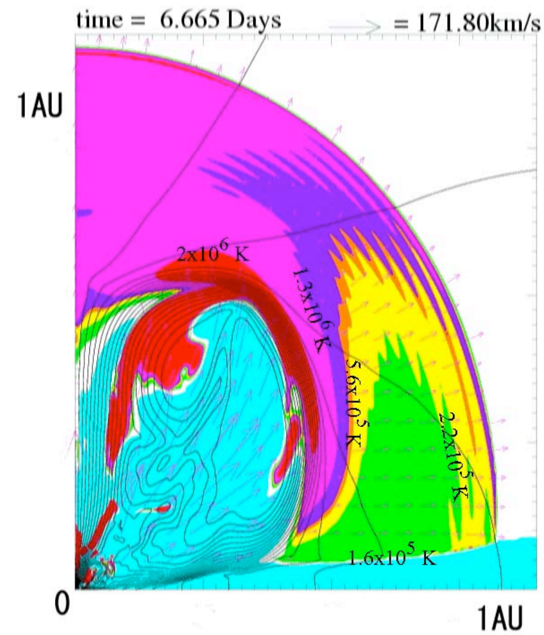

Figure 1. Temperature distribution at 6.665 day after the X-ray flare event. The total energy released by this X-ray flare is 10^{36} erg. The main part of the bubble goes upward, while a small fraction of the bubble goes toward the disk and generates shock waves.

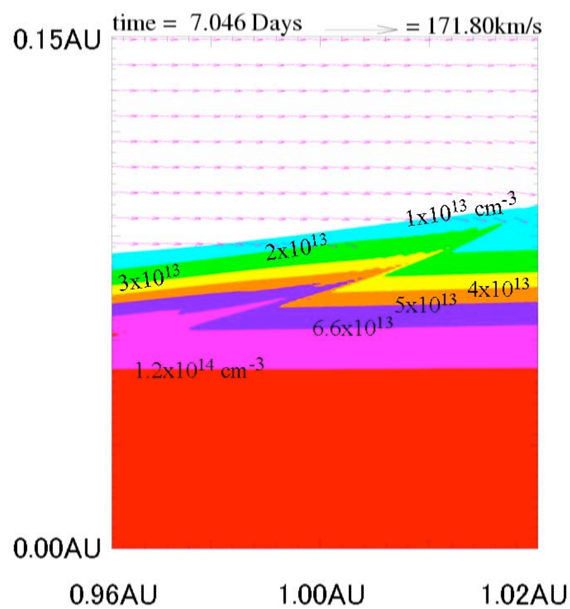

Figure 2. The density distribution at 7.046 day after the X-ray event in a 1 AU region. The density discontinuity, i.e., the shock front, is generated at about 0.07AU above the midplane. The shock front propagates with the velocity of about 100 km/s.