

X-RAY FLARE INDUCED SHOCK WAVES AND CHONDRULE FORMATION IN UPPER SOLAR NEBULA. T. Nakamoto¹, N. T. Kita², S. Tachibana³, and M. R. Hayashi⁴; ¹Center for Computational Physics, University of Tsukuba, Tsukuba 305-8577, Japan, nakamoto@rccp.tsukuba.ac.jp; ²Geological Survey of Japan, AIST, AIST Central-7, Tsukuba 305-8567, Japan, noriko.kita@aist.go.jp; ³Department of Earth and Planetary Science, University of Tokyo, Tokyo 113-0033, Japan, tachi@eps.s.u-tokyo.ac.jp; ⁴National Astronomical Observatory Japan, Mitaka 181-8588, Japan, hayshimt@cc.nao.ac.jp.

Chondrules and X-Ray Flares: Chondrules are thought to have formed through some 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 [1,2]. However, the source of shock waves and the place of the shocks in the nebula are still under debate. Proposed models include bow shocks in front of fast moving planetesimals [3], accretion shocks at the surface of nebula [4], and spiral density waves induced by the disk self-gravity [5], though every model has some drawbacks.

Here, we propose an alternative model: shock waves in the upper solar nebula induced by X-ray flares associated with the young Sun. X-ray flares, common among T Tauri stars [6], 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 of the order of 10^{30} erg s⁻¹, which is about two orders of magnitude higher than the current solar flare [6]. Such energetic flares emerge about once a day [6], almost three orders of magnitude more frequently than the current Sun. 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 [6], which is similar to the range of chondrule ages, i.e., from about 1 Myr to 3 Myr [7]. 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. Here, we focus on shock waves at the upper solar nebula in the present asteroid region (in a range 2 - 4 AU from the Sun). Although our analysis is still crude, we can see that it may be possible to form chondrules by shock waves in the upper solar nebula induced by X-ray flares.

Shock Waves in Upper Solar Nebula Induced by X-Ray Flares: 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 as

follows. The ram pressure is given by $P_{\text{ram}}(R) = \dot{M} v \cos \theta / (\Omega R^2)$, where R is the distance from the Sun, \dot{M} is the mass flux of the wind, v is the wind velocity, θ is the impact angle to the nebula surface (see Fig. 1), and Ω is the solid angle of the expanding wind. According to numerical simulations [8], the mass flux of the outflow is estimated to be $\dot{M} = 10^{-8} (v / 170 \text{ km s}^{-1}) M_{\odot} \text{ yr}^{-1}$. We assume the solid angle Ω of the expanding wind is $\pi/2$, since the wind is not spherically symmetric with respect to the star. And we assume $\cos \theta = 0.01$ [9].

As for the nebula gas pressure, assuming that the nebula is isothermal along the direction perpendicular to the nebula mid-plane, we have $P_{\text{neb}}(R, Z) = P_{\text{neb},0}(R) \exp[-(Z/h)^2]$, where h is the scale height of the nebula and $P_{\text{neb},0}(R)$ is the gas pressure at the mid-plane of the nebula. In the case of minimum-mass solar nebula model [10], we have $P_{\text{neb},0}(R) = 1.37 \times 10^{-5} (R/1 \text{ AU})^{-13/4}$ bar.

By balancing two pressures, $P_{\text{ram}}(R) = P_{\text{neb}}(R, Z)$, we can estimate the height where shock wave is expected to be present as a function of R : $Z_{\text{shock}}/h(R) = [9.47 - 1.25 \ln(R/1 \text{ AU})]^{1/2}$ (see Fig. 2). We can see that Z_{shock}/h is a decreasing function of R and in a rather narrow range from 2.78 ($R = 4 \text{ AU}$) to 2.93 ($R = 2 \text{ AU}$). Nebula gas densities at those heights before being smashed by winds are $1.36 \times 10^{-14} \text{ g cm}^{-3}$ ($R = 4 \text{ AU}$) and $3.89 \times 10^{-14} \text{ g cm}^{-3}$ ($R = 2 \text{ AU}$), respectively. Although those gas densities are much smaller than those in the nebular mid-plane, 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 [2], 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} - $10^{-13} \text{ g cm}^{-3}$ and the shock velocity is several tens km s⁻¹. In the case of winds induced by X-ray flares, it seems possible to form shock waves with such velocities, though further detailed analysis is needed to draw more rigorous conclusion.

Discussion:

Presence of Chondrule Precursors in Upper Solar Nebula: In the absence of turbulence, the chondrule precursor particles with around 0.1 mm radii may not

present in the upper solar nebula region where shock waves induced by X-ray flares should take place, because the sedimentation time scale of the dust particles is of the order of 10^4 yr [11] (shorter than the age of chondrules). However, turbulence in the nebula may rift chondrule precursor particles in the upper solar nebula for longer time. For example, using a turbulent nebula model, it was shown that 0.1-mm sized dust particles could be present as high as $3 h$, even though the concentration is very small [12]. Therefore, it is possible that chondrules are heated and formed in the upper solar nebula (at around $3 h$) by X-ray flare induced shock waves.

A Variety of Chondrule Ages: In primitive chondrites, we see chondrules with a variety of ages are randomly mixed in less than mm scale. The difference between chondrule ages in the same meteorites is at least 1 Myr [13]. This implies that heating events influence only a limited portion of chondrules and chondrule precursors at each time, otherwise, older chondrules should be reheated and their age difference should be much smaller. Our hypothetical model here may meet this requirement. The heating events take place only in the upper part of the nebula (around $3 h$), while most of the dust particles stay in the lower part of the nebula.

Frequency of Heating Events: Can this model explain abundant chondrules seen in meteorites (as much as 70% in ordinary chondrites)? It is estimated that the total number of heating events to produce such an abundant chondrules is about several times over all the dust particles in a period of 2 Myr [7]. This means that each dust particle was heated several times in the 2 Myr period averagely. For a dust particle, heating once every a few 10^5 yr is enough. This frequency is rather low. If the frequency is higher than this, it seems difficult to reconcile the chondrule age distribution: age distribution would shift to younger side. In the current hypothetical model, it is not easy for a dust particle to be in the upper solar nebula where chondrule-forming shock waves are present. Thus, the inferred low frequency of the heating event seems consistent with the model, though the possibility of being in the upper solar nebula depends on the turbulence model. Obviously, detailed investigation is needed.

Dust to Gas Mass Ratio before Shock Waves: According to an analysis for the collisional destruction among dust particles in shock waves [14], the dust/gas mass ratio before entering the shock wave is inferred to 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 may be consistent with the current model, because the dust concentration in the upper solar nebula is expected to be small.

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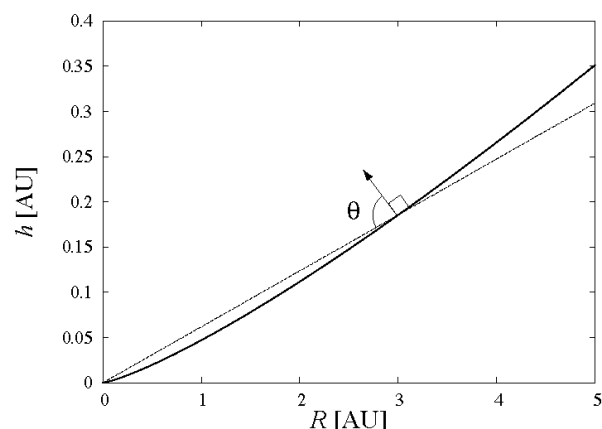


Fig.1. Scale height of a minimum mass solar nebula model [10] (solid curve). Dashed line represents a line connecting the Sun and the nebula scale height at $R = 3$ AU. The impacting angle is denoted by θ .

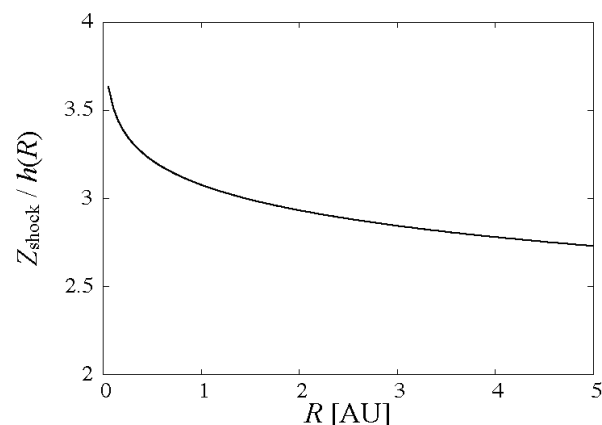


Fig.2. Expected height where shock waves are present as a function of R . Notice that the height is normalized by the scale height h at each R .