X-Ray Flare Induced Shock Waves and Chondrule Formation in the Upper Protoplanetary Disks

T. Nakamoto (U. Tsukuba), N.T. Kita (GSJ), S. Tachibana (U. Tokyo), M.R. Hayashi (NAOJ)

A New Model for Chondrule Formation

Abstract: We propose a new model for chondrule formation: shock waves in the upper protoplanetary disk induced by X-ray flares associated with the young star formed chondrules with the shock wave heating mechanism.

1. X-Ray Flares

Magnetic Flares --- Chandra observations of T Tauri Stars (Feigelson et al. 2002)

- Energetic Process: log (E_{erg}/s) = 30.3
- 10^{15} times more powerful than the current Sun
- Timing: from 0.3 Myr to ~10 Myr
- Frequency: 10^{13} times more frequent than present Sun

X-Ray Flares may be caused by Magnetic Reconnection (Hayashi et al. 1996)

2. Winds & Shocks

Winds would generate shocks in the upper region of the disk.

\[ P_{\text{X}}(R) = \frac{\dot{M}_e \cos(\theta)}{M} \]

\[ \dot{M}_e = \frac{\Omega R^2 M}{4 \pi} \]

\[ P_{\text{X}}(R,Z) = P_{\text{X}}(R) \exp(-2Z/h) \]

\[ P_{\text{X}}(R) \propto \frac{1}{R^{1.75}} \frac{1}{1 + \frac{M}{1 M_{\odot}}} \]

\[ \frac{Z}{h} = (0.47 + 1.25 \ln(R/1 AU))^{-1} \]

If there is a strong turbulence in the disk, it seems possible that large solid particles as 0.1 mm in radius can be present in the upper region of the protoplanetary disk. But it should be noticed that this estimation may depend on the turbulence model.

2.1. A variety of chondrule ages

In primitive chondrites, chondrules with a variety of ages are randomly mixed in less than mm-scale. The age difference in the same chondrite is at least 1 Myr (Moscovici et al. 2001). This implies that chondrule forming heating events influenced only a limited portion of solid particles in the early solar system at each time, otherwise, older chondrules should be reheated and their ages should be reset. Our model seems to be consistent with the variety of chondrule ages: the chondrule forming heating events take place in the upper region of the protoplanetary disk where the concentration of large solid particle is not large compared to the midplane of the disk.

2.2. Can this model explain abundant chondrules?

It is estimated that the average number of heating events per a solid particle to produce such an abundant chondrule is about several times more powerful than the present Sun.

(1) 0.1 mm sized particles in upper protoplanetary disks?

If there is a strong turbulence in the disk, it seems possible that large solid particles as 0.1 mm in radius can be present in the upper region of the protoplanetary disk. But it should be noticed that this estimation may depend on the turbulence model.

2.3. Solid to gas mass ratio

An analysis on the collisional destruction among solid particles in shock waves (Nakamoto & Miura 2004) suggests that the solid to gas mass ratio in the pre-shock region is of the order of or less than the solar value. Otherwise, chondrule size distribution in ordinary chondrites cannot be reproduced. This low solid–to–gas mass ratio is consistent with the present model: the solid concentration in the upper protoplanetary disk is expected to be lower than the solar value.

3. Chondrule Formation

Appropriate shock waves can heat solid particles enough to melt and form chondrules --- shock wave heating mechanism.

X-ray flares seem to generate appropriate shock waves in the upper region of the solar nebula: shock velocity \( \sim 40 \text{ km/s} \), pre–shock gas number density \( \sim 10^{11} \text{ cm}^{-3} \) are about \( 10^2 \sim 10^3 \text{ K/hr} \), which are consistent with values inferred from laboratory experiments.

If there are some chondrule precursor solid particles in the upper region of the solar nebula, it is expected that chondrules should be formed.

References

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Discussion

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