A Simulation of Flares in YSOs with Non-thermal Heating and Expected Hard X-ray Spectrum

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Abstract. We performed a one-dimensional hydrodynamic simulation of YSO flare loops, applying the flare mechanism for the sun. We assumed a flare loop connecting the central star and accretion disk. We found that the hard X-ray spectrum expected from our simulation has a very similar shape to the solar one observed by RHESSI, except that the energy band was 10 times higher than that of the solar flare.

1. Introduction

X-ray observations have revealed that young stellar objects (YSOs) are strong emitters of X-rays, and that frequent strong flares occur in YSOs. The temporal variabilities in X-ray during YSO flares are similar to those during solar flares (Tsuboi et al. 2000). It is widely accepted that YSOs flares are caused by magnetic activity as solar flares. However, the magnetic structure driving YSO flares are still controversial. Montmerle et at. (2000) suggested a plausible scenario: magnetic fields connecting the central star and accretion disk are twisted by differential rotation so that magnetic reconnections occur. To investigate the dynamics in such a magnetic structure, we have performed a hydrodynamical simulation.

2. Numerical Model

Our model has a central star with a radius of $4R_\odot$ and a mass of $1M_\odot$ and has an accretion disk. We also assume a magnetic loop with a constant cross section, the both ends of which cling to the central star. The loop penetrates the accretion disk, and its total length, $2L$, is $9.8 \times 10^{11}$ cm. Figure 1 shows a schematic picture of our system. We take into account the gravity of the central star and the centrifugal force, assuming the star and disk corotate as a solid body. The angular velocity is set to be equal to Keplerian angular velocity at the disk. The heating function $H(s, t)$ is $H(s, t) = H_s(s) + H_t(s, t) + H_c(s, t)$. Here, $s$ is the length measured along the loop from the surface of the star. $H_s$ is the static heating given to balance the initial radiative cooling. $H_t$ is thermal heating by the flare and takes the spatially Gaussian form; $H_c(s, t) =$
\( \frac{F_r(t)}{\sqrt{2\pi} \sigma} \exp \left[ -\left( s - s_{\text{flr}} \right)^2 / 2\sigma^2 \right] \), \( s_{\text{flr}} \) represents the energy input point, and is set to be \( L/2 \). \( H_c \) is the collisional heating by non-thermal electrons, and the heating rate is calculated in the same way as in Nagai & Emslie (1984). The particle flux \( F_p(E, t) \) takes the form of a power law with a lower cut off energy \( E_C \) and spectral index \( \delta \); \( F_p(E, t) = \left\{ (\delta - 2) F_c(t) / E_C^{\delta} \right\} \left( E / E_C \right)^{-\delta} \).

3. Results and Discussion

Figure 2 shows the temporal evolution of the density and temperature. In this case, \( F_r(t) \) and \( F_c(t) \) are set to be \( 4.74 \times 10^{10} \) erg s\(^{-1}\)cm\(^{-2}\) and \( 3.16 \times 10^{10} \) erg s\(^{-1}\)cm\(^{-2}\) for \( 0 \leq t \leq 3276 \) s, and \( F_r(t) = F_c(t) = 0 \) for \( 3276 < t \). Assuming diameter-to-length ratio 0.1, the total energy released by thermal is about \( 10^{36} \) erg that is comparable with the observed typical energy (Tsuboi et al. 2000). We also assumed \( \delta \) and \( E_C \) are 4.0 and 20 keV respectively, applying typical values in solar flare simulation (Nagai & Emslie 1984).

The dynamics is similar to that in solar flares. By the thermal conduction, the plasma in the corona is heated up to about \( 10^8 \) K. When the conduction front reaches the chromosphere of the star, where the radiative and conduction cooling are not effective, the conducted heat causes the upward enthalpy flux, i.e. evaporation flow. On the other hand, the conduction front reaching the disk causes another evaporation flow. Due to these flows, the half loop where the flare energy is released is filled with hot and dense plasma.

Figure 3 shows the hard X-ray spectra expected by our results. The right panel in the figure shows the spectrum for the case of a high energy distribution of non-thermal electrons, \( E_C = 100 \) keV and \( \delta = 4.0 \). These spectra represent only spectral energy distribution, and we do not deal with line emission and absorption. The common feature of solar and YSO flare spectrum is the spectral break, at which the spectral dominance changes from thermal to non-thermal. In our situations, the energies at which spectral break is seen in YSO flare are about 10 times higher than those in solar flare.

Figure 4 shows the distribution of the collisional heating rate by non-thermal electrons. The remarkable point is that some energy is deposited by such heating in the stellar chromosphere beyond the disk, because high energy electrons have a small cross section of the Colmnb collision and can pass through the accretion disk without so much amount of energy loss. Therefore, if we can observe our system with a certain angle, where the reconnection point is hidden by the star and disk but the footpoint far from the reconnection point can be directly seen, we may obtain the spectrum emitted only by non-thermal electrons. Such spectrum is perfectly thick target Bremsstrahlung. The discovery of such spectrum may be the evidence of the existence of the accretion disk at the halfway point of the magnetic loop.

References

Figure 1. The schematic picture of the system.

Figure 2. The temporal evolution of the number density (top) and temperature (bottom) for the case of $E_C = 20.0$ keV, $\delta = 4.0$. 
Figure 3. The expected hard X-ray spectra for the case of $E_C = 20.0$ keV, $\delta = 4.0$ (left) and $E_C = 100$ keV, $\delta = 4.0$ (right). The dashed lines represent the thermal component, and the dotted lines represent the non-thermal component of the spectrum. The solid lines are the sum of them.

Figure 4. The collisional heating rate by nonthermal electrons for the case of $E_C = 20.0$ keV, $\delta = 4.0$ (left) and $E_C = 100$ keV, $\delta = 4.0$ (right).