MHD Simulation of a Solar Flare and Derived Scaling Law between the Temperature and the Emission Measure of Stellar/Solar Flares

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Abstract. Two-dimensional magnetohydrodynamic (MHD) simulation of a solar flare including the effect of anisotropic heat conduction, radiative cooling and chromospheric evaporation based on the magnetic reconnection model is performed. The simulation results are understood by a simple scaling law for the flare temperature described as \( T_{\text{flare}} \approx \left( \frac{B^3 L}{2\pi \kappa_0 \sqrt{4\pi m n_0}} \right)^{2/7} \) where \( T_{\text{flare}} \), \( B \), \( m \), \( n_0 \), \( \kappa_0 \) are the temperature at the flare loop top, coronal magnetic field strength, mean particle mass, coronal density and heat conduction coefficient, respectively. By assuming the magnetic and gas pressure balance of the flare loops, we obtain the relation between the emission measure \( EM \) and the temperature with largest emission measure \( T \), described as

\[
EM \approx 10^{48} \left( \frac{B}{50 \text{G}} \right)^{-5} \left( \frac{n_0}{10^9 \text{cm}^{-3}} \right)^{3/2} \left( \frac{T}{10^7 \text{K}} \right)^{17/2} \text{cm}^{-3}.
\]

This relation can be applied not only to the solar flares but also to the stellar flares.

1. MHD Simulation of a Solar Flare

Solar flares are now thought to be caused by magnetic reconnection (e.g. Shibata 1996; Yokoyama & Shibata 1998). The coronal magnetic energy is converted to the thermal energy of plasma by magnetic reconnection (Fig 1; Yokoyama & Shibata 2001). This energy is transported to the chromosphere by heat conduction along magnetic field lines and causes increase in temperature and pressure of the chromospheric plasma. The pressure gradient force drives upward motion of the plasma toward the corona, i.e. chromospheric evaporation. This enhances the density of the coronal reconnected flare loops, and such evaporated plasma is considered to be the source of observed soft X-ray emission of a flare. The results show that temperature distribution is similar to the cusp-shaped structure of long-duration-event (LDE) flares observed by the soft X-ray telescope aboard Yohkoh satellite.
Figure 1. Results of the simulation. Upper and lower rows show temporal evolution of temperature and density distribution, respectively. The arrows show the velocity, and lines show the magnetic field lines. The unit of length, velocity, time, temperature, and density is 3000 km, 170 km s\(^{-1}\), 18 s, 2 \(\times\) 10\(^6\) K, and 10\(^9\) cm\(^{-3}\), respectively. In the initial condition \((t = 0)\) a dense region is located near the bottom of the simulation box in which the density is about 10\(^5\) times that of the other region.

We derive differential emission measure defined by

\[
DEM = T \left( \frac{dEM}{dT} \right)
\]

from the simulation result (Fig 2). At the beginning of the flare, hot component (> 2MK) of the DEM increases due to the chromospheric evaporation. As the evaporated plasma cools down by heat conduction and radiation, the peak of the differential emission measure moves from the X-ray temperature (a few million K) to the EUV temperature (a few times 0.1 million K).

Figure 3 shows the dependence of the temperature on the magnetic field and loop length. These results are consistently explained as follows. If we assume that the input of energy to a loop balances with the conduction cooling rate, the temperature at the loop top is \(T_{\text{flare}} \approx [QL^2/(2\kappa_0)]^{2/7}\) where \(Q\) is the volumetric heating rate (Fisher & Hawley 1990) and \(L\) is the length of the magnetic field line from the loop top to the footpoint. The heating mechanism is magnetic.
**Figure 2.** Evolution of the differential emission measure derived from the simulation results.

**Figure 3.** Temperature as functions of (left) the initial magnetic strength (right) the length of the flare loops, respectively. The dashed lines are the theoretical result (see text for the detail). The notations indicate the physical values at following points, respectively: ‘top ’ at the loop top just behind the fast-mode MHD shock, and ‘jet ’ the reconnection jet region between the slow-mode MHD shocks. The units of magnetic field, length and temperature are 3.4 G, 3000 km and $2 \times 10^6$ K, respectively.

reconnection so that the heating rate is described as $Q = B^2/(4\pi) \cdot C_A/L$ where $B$ and $C_A$ are the magnetic field strength and the Alfvén velocity of the inflow.
region, respectively. By manipulating the equations, we find

\[ T_{\text{flare}} \approx \left( \frac{B^2 C_A L}{2 \pi \kappa_0} \right)^{2/7} \approx 3 \times 10^7 \text{ K} \left( \frac{B}{50 \text{ G}} \right)^{6/7} \left( \frac{n_0}{10^9 \text{ cm}^{-3}} \right)^{-1/7} \left( \frac{L}{10^9 \text{ cm}} \right)^{2/7} \]

where \( T_{\text{flare}} \), \( B \), \( \rho \), \( \kappa_0 \) are the temperature at the flare loop top, coronal magnetic field strength, coronal density and heat conduction coefficient, respectively.

2. Scaling Law between the Temperature and the Emission Measure of Stellar/Solar flares

We extended this result to apply to the stellar flares (Shibata & Yokoyama 1999). Recent space observations of stellar flares as well as solar flares have revealed that there is a universal correlation between the peak temperature \( (T) \) of a flare and its volume emission measure \( (EM = n^2 V) \), such that \( EM \) increases with increasing \( T \), where \( n \) is the electron number density and \( V \) is the volume (Stern 1992, Feldman et al. 1995, Yuda et al. 1997). This correlation is extrapolated to not only solar microflares (Shimizu 1995) but also protostellar flares (Koyama et al. 1996, Tsuboi et al. 1998).

As a result of the chromospheric evaporation, the flare loop density increases to \( n \). This evaporated plasma is the source of X-ray emission;

\[ EM \approx n^2 L^3. \]

Here, we assumed \( V \approx L^3 \). Since this evaporated plasma has high gas pressure, we have to assume that magnetic pressure of the reconnected loop must be larger than the gas pressure of evaporated plasma to confine evaporated plasma in the loop and maintain stable flare loop. From this, it may be reasonable to assume

\[ 2nkT \approx \frac{B^2}{8\pi}, \]

as an upper limit of gas pressure. Eliminating \( n \) and \( L \) from above equations, we find

\[ EM \approx 10^{48} \left( \frac{B}{50 \text{ G}} \right)^{-5} \left( \frac{n_0}{10^9 \text{ cm}^{-3}} \right)^{3/2} \left( \frac{T}{10^7 \text{ K}} \right)^{17/2} \text{ cm}^{-3}, \]

which explains well the observed correlation between \( EM \) and \( T \) in the range of \( 6 \times 10^6 \text{ K} < T < 10^8 \text{ K} \) and \( 10^{44} < EM < 10^{55} \text{ cm}^{-3} \) from solar microflares to protostellar flares, if the magnetic field strength of a flare loop, \( B \), is nearly constant for solar and stellar flares (Fig 4).

References

Figure 4. The log-log plot of emission measure vs. electron temperature of solar flares (from Feldman et al. 1995), solar microflares observed by Yohkoh SXT (from Shimizu 1995), four stellar flares (asterisks, from Feldman et al. 1995), a protostellar flare (diamond, class 1 protostar far IR source R1 in the R CrA cloud, from Koyama et al. 1996), a T-Tauri stellar flare (diamond, weaklined T-Tauri star V773 Tau, from Tsuboi et al. 1998), and a stellar flare on AB Dor (K0 IV ZAMS single star) by BeppoSax (cross, Pallavicini 1998). The $EM-T$ relation curves based on theoretical equation ($EM \propto B^{-5}T^{17/2}$) are superposed on the $EM-T$ diagram for $B = 15, 50, 150, \text{and} 500 \text{ G}$. The $L = \text{constant curves} \ (EM \propto L^{5/3}T^{8/3})$ are also superposed on this diagram (dashed lines).

Conference Summary