Origin of Universal Correlation between Temperature and Emission Measure for Solar/Stellar Flares

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We study the reconnection and the chromospheric evaporation in flares using the numerical code including nonlinear anisotropic heat conduction effect (Yokoyama & Shibata 1998; 2001). The two-dimensional, nonlinear, time-dependent, resistive, compressible MHD equations are solved. The evolution from the rise phase to (the early part of) the decay phase of a solar flare is qualitatively reproduced in this simulation. Based on the results, we obtained a relationship between the flare temperature and the coronal magnetic field strength. If we assume that the input of energy to a loop balances with the conduction cooling rate, the temperature at the loop apex is

\[ T_A \approx \left( \frac{2QL^2}{\kappa_0} \right)^{2/7} \]

where \( Q \) is the volumetric heating rate, \( L \) is the half-length of the loop, and \( \kappa_0 = 10^{-6} \) CGS is the Spitzer’s thermal conductivity constant. In our simulations, the heating mechanism is magnetic reconnection so that the heating rate is described as

\[ Q = B^2 / (4\pi) \cdot V_{in} / L \cdot 1 / \sin \theta, \]

where \( B \) is the coronal magnetic field strength, \( V_{in} \) is the inflow velocity (\( \approx 0.1V_A \) from our result and also from Petschek’s theory), and \( \theta \) is the angle between the slow-mode MHD shock and the loop and is approximately given by \( \sin \theta \approx V_{in} / V_A \). By manipulating the equations, we find

\[ T_A \approx \left( \frac{B^3L}{2\pi\kappa_0\sqrt{4\pi\rho}} \right)^{\frac{2}{7}} \propto B^{\frac{2}{7}} \propto \beta^{-\frac{1}{7}}, \]

where \( \rho \) is the mass density of the corona. The simulation results show very good agreement with this scaling law.

We also develop a theory to explain the observed universal correlation between flare temperature \( T \) and emission measure \( EM = n^2V \) for solar and stellar flares (including solar microflares observed by Yohkoh as well as protostellar flares observed by ASCA), where \( n \) is the electron density and \( V \) is the volume (Figure 1; Shibata & Yokoyama 1999). The theory is based on the above magnetic reconnection model with heat conduction and chromospheric evaporation, assuming that the gas pressure of a flare loop is comparable to the magnetic pressure. This theory predicts the relation

\[ EM \propto B^{-5}T^{17/2} \]
Figure 1. The log-log plot of emission measure vs. electron temperature of solar flares, solar microflares, four stellar flares (asterisks), a protostellar flare (diamond, class 1 protostar far IR source R1 in the R CrA cloud), a T-Tauri stellar flare (diamond, weak-lined T-Tauri star V773 Tau), and a stellar flare on AB Dor (K0 IV ZAMS single star). The $EM - T$ relation curves ($EM \propto B^{-5} T^{17/2}$) are superposed on the $EM - T$ diagram. The $L = \text{constant}$ curves (dashed lines; $EM \propto L^{5/3} T^{8/3}$) are also superposed on this diagram.

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.

References