Highly Energetic Physical Processes and
Mechanisms for Emission from Astrophysical Plasmas
IAU Symposium, Vol. 195, 2000
P. C. H. Martens, S. Tsuruta, and M. A. Weber, eds.

Numerical Simulations of Solar Flares

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We study reconnection and chromospheric evaporation in flares using a numerical code including nonlinear, anisotropic heat conduction (Yokoyama & Shibata 1998). 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. We assume that the energy input to a loop balances with the conductive cooling rate, that the temperature at the loop apex is $T_{\rm A} \approx (2QL^2/\kappa_0)^{2/7}$, where Q is the volumetric heating rate, that L is the half-length of the loop, and that the Spitzer thermal conductivity constant is $\kappa_0 = 10^{-6}$ CGS. In our simulations, the heating mechanism is magnetic reconnection, so the heating rate is described as $Q = B^2/(4\pi) \cdot V_{\rm in}/L \cdot 1/\sin\theta$, where B is the coronal magnetic field strength, $V_{\rm in}$ is the inflow velocity ($\approx 0.1\ V_{\rm A}$ from our result and also from Petschek's theory), and θ is the angle between the slow-mode MHD shock and the loop and is approximately given by $\sin\theta \approx V_{\rm in}/V_{\rm A}$. By manipulating the equations, we find

$$T_{\rm A} \approx \left(\frac{B^3 L}{2\pi\kappa_0\sqrt{4\pi\rho}}\right)^{\frac{2}{7}} \propto B^{\frac{6}{7}} \propto \beta^{-\frac{3}{7}}, \tag{1}$$

where ρ 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 universally observed correlation between flare temperature T and emission measure, $\mathrm{EM} = n^2 V$, 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

$$\mathrm{EM} \propto B^{-5} T^{17/2}, \tag{2}$$

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

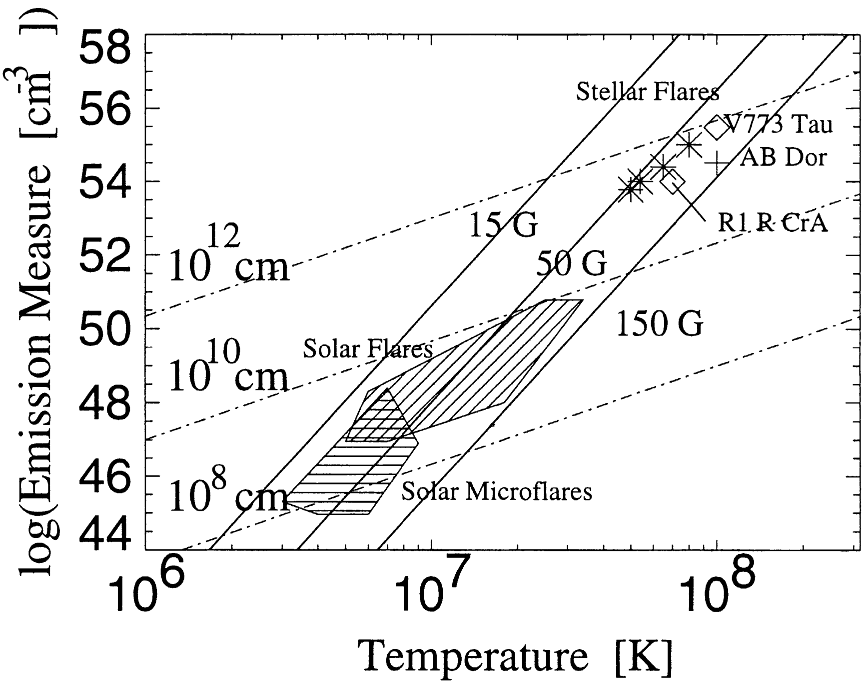

Figure 1. The log-log plot of emission measure (EM) vs. electron temperature of solar flares, solar microflares, four stellar flares (asterisks), a protostellar flare (diamond; class 1 protostar far-IR source R1 in the R CrA cloud), a T-Tauri stellar flare (diamond; weak-lined T-Tauri star V773 Tau),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

References

Yokoyama, T., & Shibata, K. 1998, ApJ, 494, L113

Shibata, K., & Yokoyama, T. 1999, ApJ, 526, L49

https://doi.org/10.1017/S0074180900163466 Published online by Cambridge University Press