Candidate coronal mass ejection heating mechanisms

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Abstract

Several recent observational results suggest that coronal mass ejection (CME) plasma is heated even after leaving the flare site. The source of this heating is probably the magnetic field, but the mechanisms that convert magnetic to thermal energy during these events are not well understood. In the context of CMEs observed by SOHO/UVCS and analyzed using a time-dependent ionization code, we assess the efficacy of several candidate mechanisms, including heating by the CME current sheet, kink/shearing instabilities of the flux rope, turbulence, thermal conduction, energetic particles, and wave heating. Further tests of these models require investigating many events using a standardized method, so we discuss progress on automating this time-dependent ionization technique to constrain heating rates for a large number of CMEs.

Introduction

The energy budget of CMEs is an emerging area of research.

• While kinetic and potential energies are relatively straightforward, finding the heating rates and thermal energy content is more challenging.

• The Ultraviolet Coronagraph Spectrometer (UVCS) aboard the Solar and Heliospheric Observatory (SOHO) provides the opportunity to analyze the thermal component of the energy budget (e.g., Akmal et al. 2001; Lee et al. 2009; Landi et al. 2010).

• The ejected material is not in ionization equilibrium, so it is necessary to track the ionization states of the plasma from the flare site to the position observed by UVCS.

• Because of a lack of diagnostics, the magnetic energy is even more difficult to obtain than the thermal energy and heating rates.

Observations

White light coronagraph observations were taken by MLSO/MK4 (left) and LASCO C2 and C3 (right) of a CME on 28 June 2000. The LASCO CME catalog gives a mass of $\sim 3 \times 10^{15}$ g and an in-plane velocity of $\sim 1200$ km/s for the leading edge.

Measurements with UVCS were taken with a two minute cadence throughout this event. The UVCS slit was positioned at PA = $295^\circ$ at $2.3 R_E$ above the northwest limb. Below are spectra taken at 20:12 UT. Shown is Blob F.

The density at the UVCS slit is found using one of two methods:

1. The ratio of the [O vi] $\lambda 1218$ forbidden line to the [O vi] $\lambda 1238$ intercombination line (Akmal et al. 2001).
2. Radiative pumping of the [O vi] $\lambda 1302,1308$ doublet chromosphere lines $\lambda_\lambda 1302,1308$ (Noci et al. 1987; Raymond & Ciaramella 2004).

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Recent simulations suggest that most of the outflow energy is directed upwards towards the rising flux rope (e.g., Reeves et al. 2010; Murphy 2010). Reconnection heating cannot be parameterized in a 1-D model. Constraints on this heating mechanism require comparing observations to time-dependent ionization analyses of MHD simulations.

Constrains on plasma heating

Constraints on plasma heating are found by comparing UVCS observations to a time-dependent ionization code (Akmal et al. 2001).

• Starting from a range of initial densities and temperatures and assuming homologous expansion, the code tracks ionization fractions until it reaches the UVCS slit.

• Several different heating parameterizations are used including an exponential wave heating model by Allen et al. (1998), heating proportional to $n$ and $T^2$, and the model of Kumar & Rust (1996). The heating counteracts radiative losses and cooling by adiabatic expansion.

• The observed line ratios from the UVCS diagonal spectral feature are used as constraints for the model. We assume that the $O$ VI and $O$ I emission are from the same source and use the other line strengths as upper limits.

• The total heating consistent with UVCS observations for each blob are $(10^{14}$ erg g$^{-1}$).

<table>
<thead>
<tr>
<th>Blob</th>
<th>$n$ (cm$^{-3}$)</th>
<th>$T$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100-200</td>
<td>10,000</td>
</tr>
<tr>
<td>B</td>
<td>500-1000</td>
<td>3000</td>
</tr>
<tr>
<td>C</td>
<td>1000-2000</td>
<td>2000</td>
</tr>
<tr>
<td>D</td>
<td>2000-4000</td>
<td>1000</td>
</tr>
<tr>
<td>E</td>
<td>4000-6000</td>
<td>500</td>
</tr>
<tr>
<td>F</td>
<td>6000-8000</td>
<td>300</td>
</tr>
</tbody>
</table>

where the kinetic energies assume the velocity given by O VI pumping (lower limits in parentheses).

• The best constrained feature (Blob F) shows that the total heating required is comparable to or greater than the kinetic energy of the feature.

Standardization of this analysis

This time-dependent ionization technique has been used to constrain heating during several events (Akmal et al. 2001; Ciaramella et al. 2001; Lee et al. 2009; Landi et al. 2010). The assumptions made for each of these events differ, thus complicating comparisons between events. To enable straightforward comparisons, we are implementing a standardized method which we will apply to a set of 10-20 events.

1. Identify candidate CMEs observed by UVCS.
2. Run a script to find features with good O VI or O III density diagnostics.
3. Run a script to find line strengths for these features.
4. Use white light observations to identify these features, find velocity curves, and column densities.
5. When possible, use EIT and other observations to provide further constraints.

Conclusions

• The total heating of CMEs is comparable to or greater than the kinetic energy of the ejecta, and is an important term in the CME energy budget.

• Candidate heating mechanisms include upflow from the CME current sheet, wave heating, energetic particles, thermal conduction, large-scale MHD instabilities, dissipation of turbulence, and small-scale reconnection in the rising flux rope.

• Observations of the 28 June 2000 CME suggest that heating via the kink instability, thermal conduction, colliding flows, and energetic particles are unlikely to be significant.

• To better understand CME heating, we will perform a standardized version of this analysis for $\sim 10-20$ events.

References


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