Plasma Heating Rates for a Coronal Mass Ejection on 28 June 2000

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Abstract

Several recent observational results suggest that the heating of coronal mass ejections (CMEs) continues even after the ejected material leaves the flare site. To investigate the importance of heating in the energy budget of these events, we analyze a partial halo CME on 28 June 2000 that was observed by the UVCS, LASCO, and EIT instruments aboard SOHO and the MK4 coronagraph at the Mauna Loa Solar Observatory (MLSO). Heating rates are estimated by using a time-dependent ionization code with the densities derived from UVCS measurements as the outer boundary condition. The energy deposited into heat is then compared to the kinetic energy of the CME estimated from LASCO, MK4, and UVCS observations. We assess the relevance of theories of flux rope heating and consider connections with similar phenomena in laboratory plasma experiments.

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 state 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.

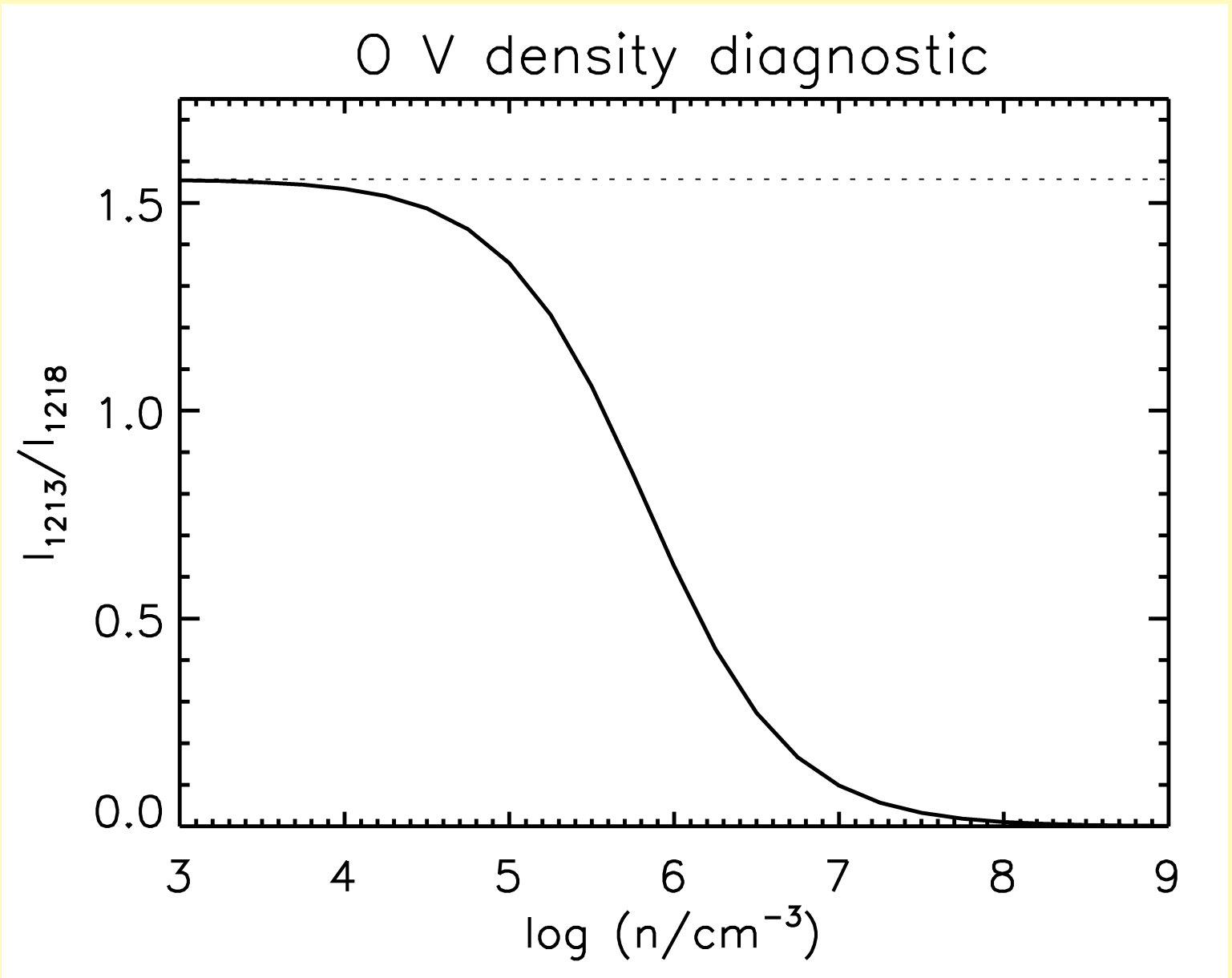
The fast partial halo CME of 28 June 2000 has been investigated previously in three different efforts.

- Raymond & Ciaravella (2004) derive densities from radiative pumping of the O VI doublet (see below). Estimates range from 1.28×10^6 to 3.91×10^7 cm^{-3}.
- Ciaravella et al. (2005) use UVCS and LASCO observations to identify the leading edge of this CME as a fast mode shock front.
- Maričić et al. (2006) report on the plane-of-sky kinematics of this event for the prominence and leading edge using LASCO and MLSO.

Density Diagnostics

We use two independent methods for finding the density from UVCS observations.

1. The ratio of the O V λ1213.85 forbidden line to the O V λ1218.39 intercombination line is a reliable number density diagnostic for $n \sim 10^6$–10^7 cm^{-3}.



2. The ratio of O VI λ1031.91 to O VI λ1037.61 will be 2:1 when collisional excitation dominates. Departures from this ratio are due to radiative pumping of O VI λ1037 by C II $\lambda\lambda$1036.3, 1037.0 near velocities of 172 and 371 km s^{-1}, O VI λ1037 by O VI λ1032 near velocities of 1650 km s^{-1}, or O VI λ1032 by Ly β near velocities of 1810 km s^{-1}. In order, the inferred densities for these pumping mechanisms are

$$n_e \sim 0.3 \times 10^6 \frac{R}{2-R} \text{ cm}^{-3} \qquad \text{(pumping by C II)}$$

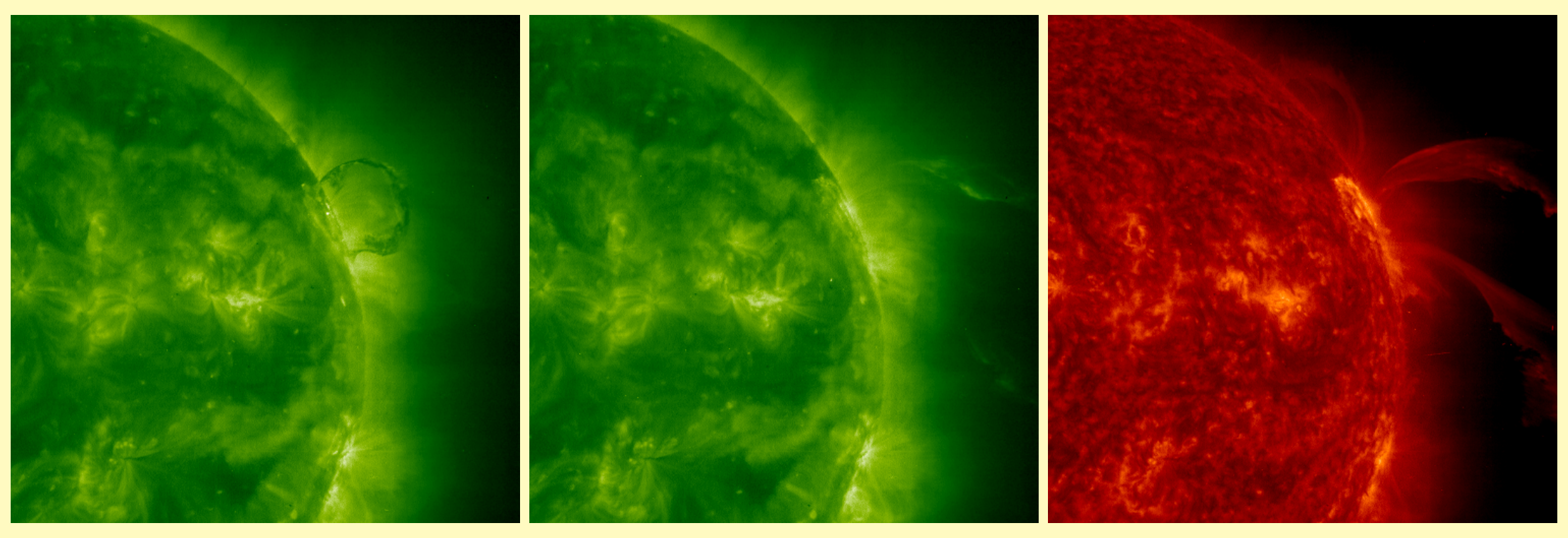
$$n_e \sim 3.3 \times 10^6 \frac{R}{R-2} \text{ cm}^{-3} \qquad \text{(pumping by O VI)}$$

$$n_e \sim 1.6 \times 10^6 \frac{R}{2-R} \text{ cm}^{-3} \qquad \text{(pumping by Ly } \beta\text{)}$$

(see Li et al. 1998; Raymond & Ciaravella 2004).

EIT Observations

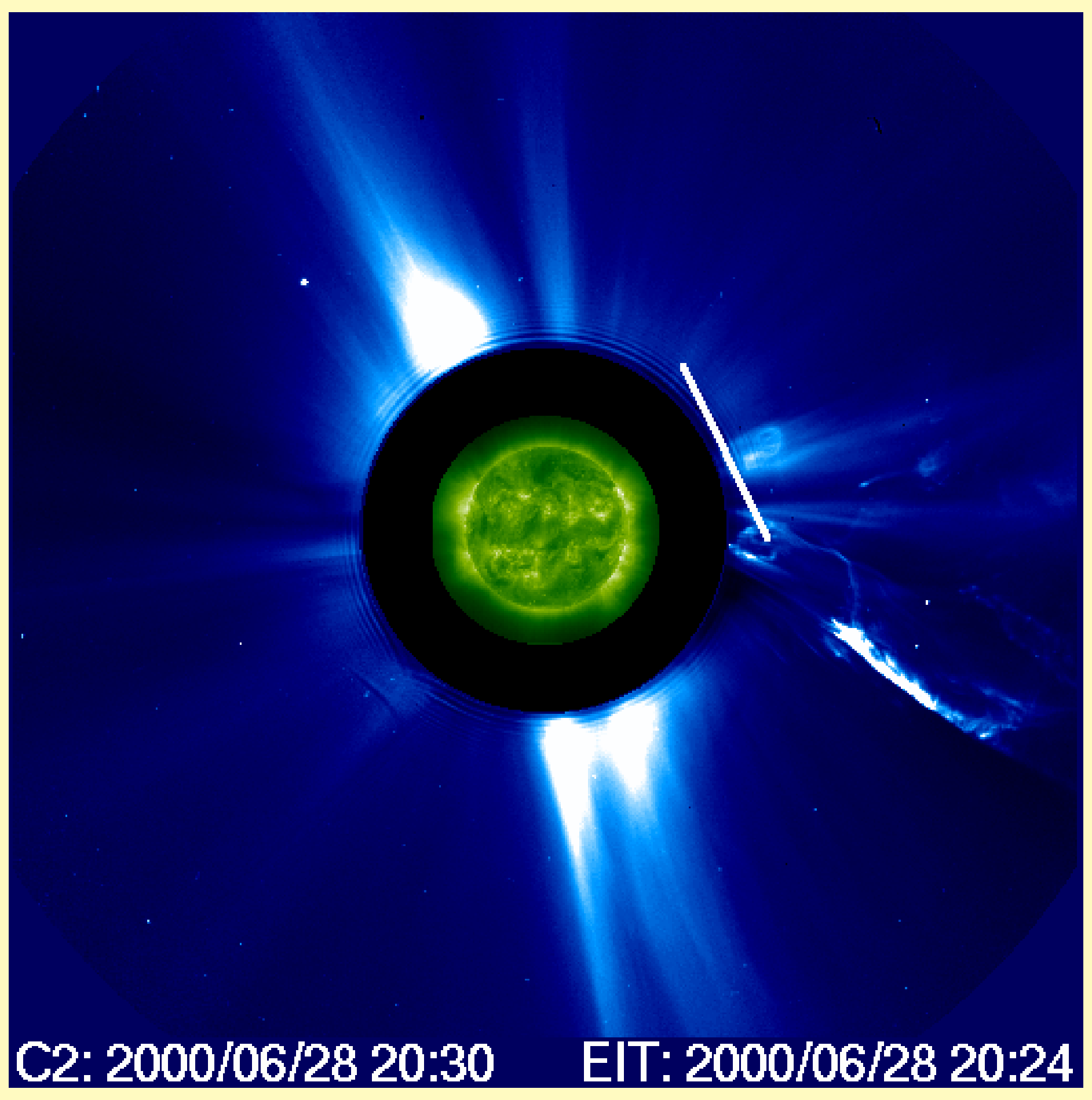
The Extreme Ultraviolet Imaging Telescope (EIT) captured a prominence that started to rise around 18:00 UT and began to erupt around 18:30 UT.



EIT 195 Å images of the rising filament at 18:48 UT (*left*) and the eruption at 19:13 UT (*middle*). The 304 Å image at 19:19 UT shows strands of cooler plasma extending beyond the field of view (*right*).

White Light Observations

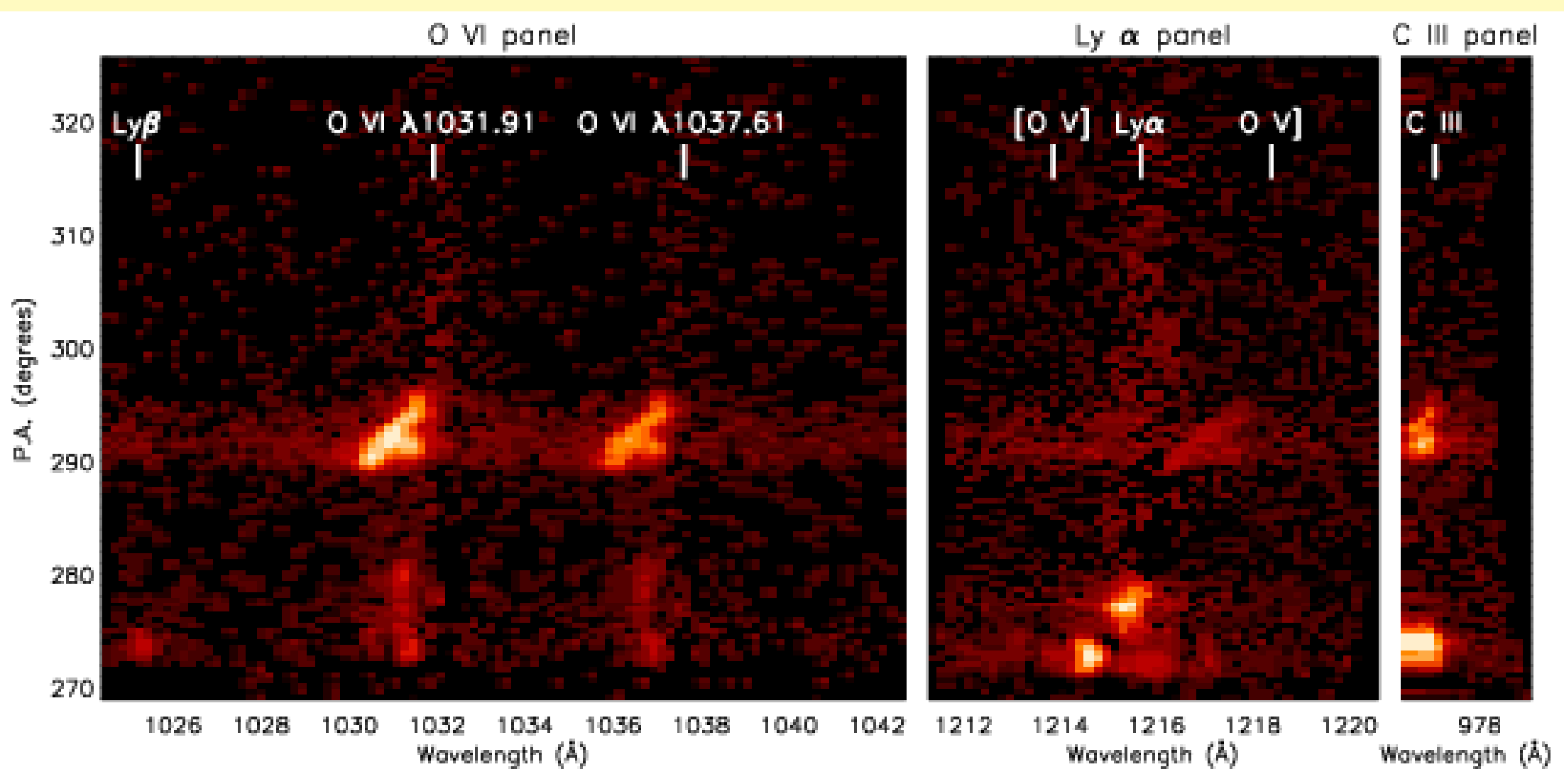
White light coronagraph observations were taken by MLSO/MK4 and LASCO C2 and C3. The LASCO CME catalog gives a mass of $\sim 7.3 \times 10^{15}$ g and an in-plane velocity of ~1200 km/s for the leading edge.



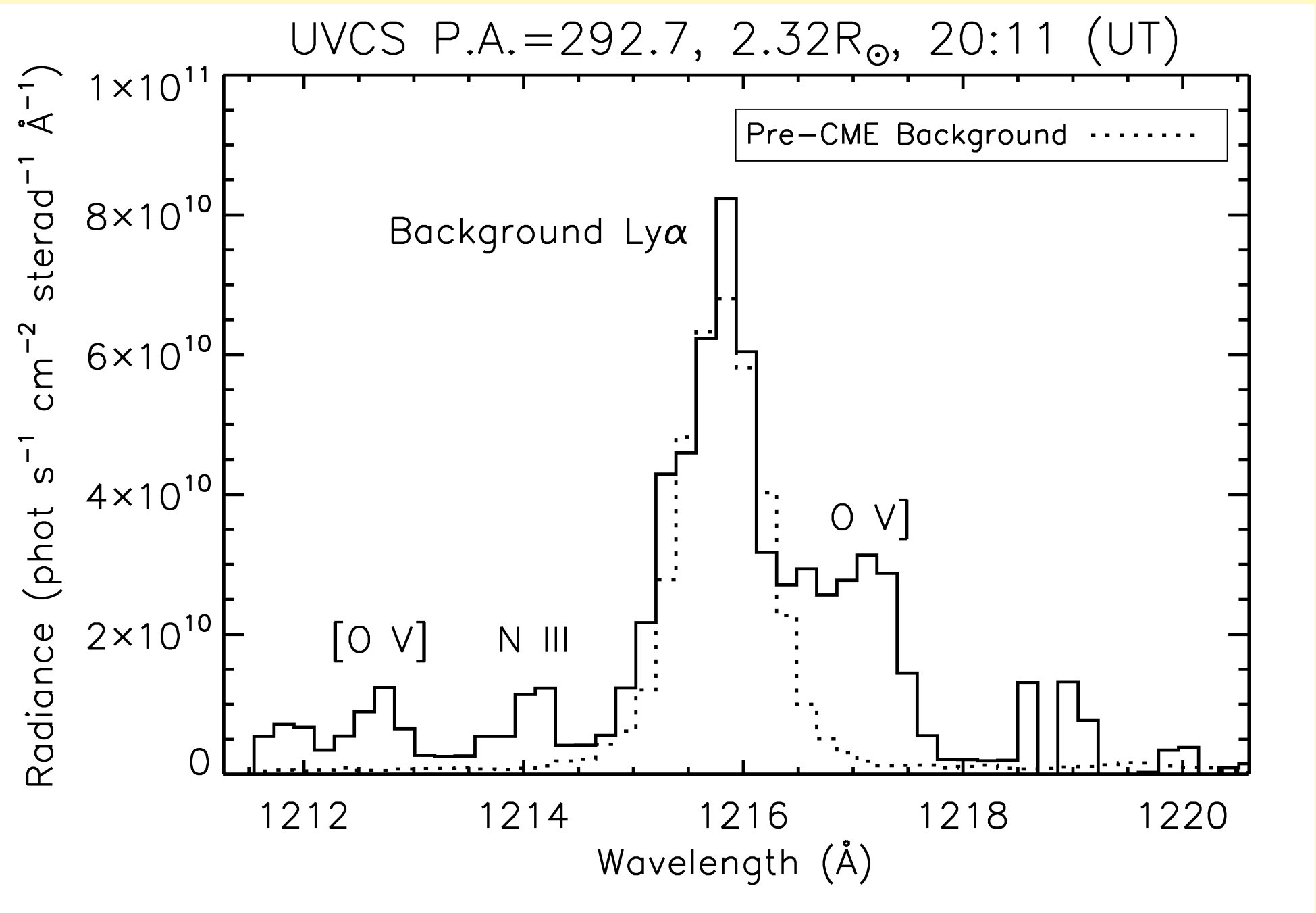
The UVCS slit position in the figure is denoted by the white line. The O V and O VI diagonal feature described below is associated with the rising loop above the center of the slit.

UVCS Observations

Measurements with UVCS were taken with a two minute cadence throughout this event. The UVCS slit was positioned at P.A. $= 295^\circ$ at $2.32 R_\odot$ above the northwest limb. Below are spectra taken at 20:12 UT.



The pre-CME background was subtracted in the above image. To find heating rates, we focus on the diagonal structure near P.A. $= 292^\circ$ seen in O V and O VI but not in Lyα.



The primary channel N III λ991 line appears at ~1214 Å in the redundant Lyα channel. From the ratio of O V lines, we adopt a density of $\sim 4 \times 10^6$ cm^{-3}.

Plasma Heating Rates

Plasma heating rates 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 a wave heating model by Allen et al. (1998), heating proportional to n and n^2, and the model of Kumar & Rust (1996).
- The observed line ratios from the UVCS diagonal spectral feature are used as constraints for the model. We assume that the O V and O VI emission are from the same source and use the other line strengths as upper limits.
- Using the observed line ratios from UVCS as constraints on the models, we find the plasma heating rates to be ~900–2000 eV/proton. The best models have initial densities of 10^8–10^9 cm^{-3} and a wide range of initial temperatures.
    - The wave heating parameterization gives $T_0 \sim 2 \times 10^6$ K whereas the Kumar & Rust (1996) model gives $T_0 \sim 5 \times 10^4$ K.
- Estimating an in-plane velocity of ~175 km s^{-1} from UVCS and LASCO and a O VI blueshift of ~314 km s^{-1}, the kinetic energy is ~674 eV/proton.
- The models by Kumar & Rust (1996) and Wang et al. (2009) assume self-similar expansion of flux ropes; both predicting significant amounts of heating comparable to observations. However, this assumption is violated during the early stages of a CME and when the expanding flux ropes kink.
- It is probable that analogous heating mechanisms occur in laboratory plasmas during kink and/or tearing behavior. Relevant devices that study the formation and evolution of flux ropes include RSX at LANL, MRX at PPPL, LAPD at UCLA, and the Caltech spheromak experiment.

Future Work

Several steps remain for the analysis of this event.

- Additional blobs with accurate densities will be compared against the ionization code.
- LASCO and MLSO white light observations will be used to constrain column densities.
- EIT observations will constrain temperatures and densities in the model output at low heights.
- Yohkoh observations might constrain the magnetic free energy before and after the CME.

After completing our investigation of this event, we will continue to extend the sample of CME energy budgets using UVCS and other observations.

- We have identified more than 20 CMEs observed by UVCS which show promising density diagnostics and should be amenable to this form of analysis.
- We will attempt to analyze a large number of events using automated methods instead of case by case.

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