OBSERVATIONAL EVIDENCE OF GENTLE AND EXPLOSIVE CHROMOSPHERIC EVAPORATION

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ABSTRACT

Observational evidence of chromospheric evaporation during the impulsive phase of two solar flares is presented using data from the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) and the Coronal Diagnostic Spectrometer (CDS) onboard SOHO. For the first time, co-spatial imaging and spectroscopy have been used to observe both gentle and explosive evaporation processes within HXR emitting regions. For a GOES C9.1 flare, a flux of nonthermal electrons of \(\geq 5 \times 10^9\) ergs cm\(^{-2}\) s\(^{-1}\) was found to produce low-velocity upflows of 13\(\pm\)16, 16\(\pm\)18, and 110\(\pm\)58 km s\(^{-1}\) in the cool He I and O V emission lines and the 8 MK Fe XIX line, respectively, indicative of gentle evaporation. An M2.2 flare, on the other hand, showed downflows of 36\(\pm\)16 and 43\(\pm\)22 km s\(^{-1}\) in the He I and O V lines and high-velocity upflows of 230\(\pm\)38 km s\(^{-1}\) in the Fe XIX line, for an electron flux value which is an order of magnitude higher (\(\geq 4 \times 10^{10}\) ergs cm\(^{-2}\) s\(^{-1}\)) indicative of an explosive process. These findings confirm that the dynamic response of the solar atmosphere is sensitively dependent on the flux of incident electrons as predicted by current hydrodynamical simulations.

Key words: Sun: atmospheric motions, Sun: flares, Sun: UV radiation, Sun: X-rays, \(\gamma\)-rays.

1. INTRODUCTION

Current solar flare models (Antiochos & Sturrock 1978; Fisher, Canfield, & McAlpine 1984, 1985a,b,c; Mariska, Emslie, & Li 1989) predict two types of chromospheric evaporation processes. “Gentle” evaporation occurs when the chromosphere is heated either directly by non-thermal electrons, or indirectly by thermal conduction. The chromospheric plasma subsequently loses energy via a combination of radiation and low-velocity hydrodynamic expansion. “Explosive” evaporation takes place when the chromosphere is unable to radiate energy at a sufficient rate and consequently expands at high velocities into the overlying flare loops. The overpressure of evaporated material also drives low-velocity downward motions into the underlying chromosphere, in a process known as chromospheric condensation.

From a theoretical perspective, Fisher, Canfield, & McAlpine (1985a) investigated the relationship between the flux of non-thermal electrons (\(F\)) and the velocity response of the atmosphere for the two classes of evaporation. For gentle evaporation, non-thermal electron fluxes of \(\leq 10^{10}\) ergs cm\(^{-2}\) s\(^{-1}\) were found to produce upflow velocities of tens of kilometres per second. In contrast, explosive evaporation was found to be associated with higher non-thermal electron fluxes (\(F \geq 3 \times 10^{10}\) ergs cm\(^{-2}\) s\(^{-1}\)) which drive both upflows of hot material at velocities of several hundred kilometres per second and downflows of cooler material at tens of kilometres per second.

Observationally, previous studies have identified blue-shifted Soft X-Ray and EUV lines indicative of chromospheric evaporation. Using the Bent Crystal Spectrometer onboard the Solar Maximum Mission, Antonucci & Dennis (1983) and Zarro & Lemen (1988) reported upflow velocities of 400 km s\(^{-1}\) and 350 km s\(^{-1}\), respectively, in Ca XIX lines (3.1–3.2 Å). More recently, Czyzkowska et al. (1999), Teriaca et al. (2003), and Del Zanna et al. (2006) observed velocities of 140–200 km s\(^{-1}\) in Fe XIX (592.23 Å), using the Coronal Diagnostic Spectrometer (CDS; Harrison et al. 1995) onboard the Solar and Heliospheric Observatory (SOHO). Simultaneous upflows and downflows during a Hard X-Ray (HXR) burst indicative of explosive evaporation have been observed using CDS and Yohkoh/Hard X-Ray Telescope by Brosius & Phillips (2004). While these observed upflows may suggest an explosive process, they were unable to provide a measurement of the flux of electrons responsible, nor the spatial relationship between the two.

Evidence for gentle evaporation, on the other hand, has most often been observed during the decay phase, when the upflows are driven by thermal conduction rather than electron beam heating (Schmieder et al. 1987; Zarro & Lemen 1988; Czyzkowska et al. 2001; Berlicki et al. 2002).
In each of these studies it was concluded that the late phase evaporation was caused by heat conduction along field lines connecting the chromosphere to the corona.

Here we present co-spatial and co-temporal observations of chromospheric evaporation during the impulsive phase of two solar flares using simultaneous data taken by the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) and CDS.

2. OBSERVATIONS AND DATA ANALYSIS

This study focuses on a GOES C9.1 flare which began at 11:40 UT on 2002 July 15, and an M2.2 flare, which began at 12:44 UT on 2003 June 10. The lightcurves for each event as observed by RHESSI are shown in Figure 1. These events were selected from a sample of approximately 50 flares jointly observed by RHESSI and CDS. The limited field of view, cadence, and operating schedule of CDS, coupled with RHESSI nighttime and South Atlantic Anomaly passes, make simultaneous observations by the two instruments quite rare.

2.1. The Coronal Diagnostic Spectrometer (CDS)

The CDS observations reported here were obtained with the FLARE AR observing sequence. FLARE AR contains five ≤4 Å wide spectral windows centered on He I (584.33 Å; log T = 4.5), O V (629.73 Å; log T = 5.4), Mg X (624.94 Å; log T = 6.1), Fe XVI (360.76 Å; log T = 6.4), and Fe XIX (592.23 Å; log T = 6.9). Each raster consists of 45 slit positions, each ~15 seconds long, resulting in an effective cadence of ~11 minutes. The slit itself is 45′′×180′′ yielding a ~180′′×180′′ field of view. The spectrum from each CDS pixel was fitted with a broadened Gaussian profile (Thompson, 1999), for each of the five spectral windows. Velocity maps were created by measuring Doppler shifts relative to quiet-Sun spectra, which were assumed to be emitted by stationary plasma. A heliographic correction was also applied, due to the longitude of the observations and assuming purely radial flows.

2.2. The Reuven Ramaty High Energy Spectroscopic Imager (RHESSI)

RHESSI is an imaging spectrometer capable of observing X-ray and γ-ray emission over a wide range of energies (~3 keV–17 MeV). During both events the thin attenuators on RHESSI were in place thus limiting the energy range to ≥6 keV. Flare emission was not observed above 50–60 keV. Both the RHESSI images and spectra were obtained over a timerange which was determined by the duration that blushifts were observed by CDS in the Fe XIX line. The RHESSI spectra were fitted assuming an isothermal distribution at low energies, and thick-target emission at higher energies (top panel of Figures 2 and 3). The total power of non-thermal electrons above the low energy cut-off (εc) was calculated from $P(ε ≥ εc) = \int_{εc}^{\infty} f_ε(ε) de$ ergs s$^{-1}$, where $f_ε(ε) \sim ε^{-δ}$ electrons keV$^{-1}$ s$^{-1}$ is the thick-target electron injection spectrum and δ is the associated spectral index (Brown, 1971). RHESSI images were reconstructed using the Pixon algorithm (Hurford et al., 2002) and were used to measure the source size of the HXR emitting region. The total flux of the nonthermal electrons was then found by dividing the power by the area.

3. RESULTS

3.1. Evidence of Gentle Evaporation

For the C9.1 event, the thick-target model solution, consistent with the RHESSI photon spectrum, produced an electron distribution with a low-energy cutoff of ~20 keV.
Figure 2. X-ray spectrum and velocity maps for the C9.1 flare. Top Panel: Portion of the RHESSI spectrum integrated over the time range that blueshifts were observed. The energy range 6–50 keV lying between the vertical dot-dashed lines was fitted assuming an isothermal component (dotted curve) and a thick-target bremsstrahlung component (dashed curve). Bottom Panels: Velocity maps in He I and Fe XIX. Downflows are indicated by red pixels, while upflows are indicated by blue pixels. The solid contours denote the RHESSI 16–50 keV emission at 10% and 40% of the peak intensity, while the dotted contour shows the 6–16 keV emission at 5% of the peak intensity.

and a power-law index of $\sim 5.2$. From the properties of the inferred electron spectrum, the total power of non-thermal electrons was found to be $\sim 8 \times 10^{37}$ ergs cm$^{-2}$ s$^{-1}$. The reconstructed 16–50 keV image yielded an upper limit to the HXR source size of $\sim 1.8 \times 10^{18}$ cm$^2$, and the resulting flux of non-thermal electrons was therefore found to be $\geq 5 \times 10^{38}$ ergs cm$^{-2}$ s$^{-1}$. The bottom panel of Figure 2 shows the corresponding spatial distribution of velocities seen in each of the He I and Fe XIX lines. Net upflows of $13 \pm 16$ km s$^{-1}$ were observed in the He I maps (and $16 \pm 18$ km s$^{-1}$ in O V) by averaging over all CDS pixels within the 16–50 keV 10% contour as observed by RHESSI. Moderately strong upflows of $110 \pm 58$ km s$^{-1}$ were observed in the Fe XIX map by averaging over the same area. No significant flows were observed in the Mg X and Fe XVI lines. (See Milligan et al. 2006b.)

3.2. Evidence of Explosive Evaporation

For the M2.2 event, the thick-target model fitted to the RHESSI spectrum was consistent with an electron distribution having $\epsilon \sim 20$ keV and $\delta \sim 7.3$. The total power in non-thermal electrons was therefore $1 \times 10^{38}$ ergs s$^{-1}$. Using the reconstructed 25–60 keV image, the upper limit to the source size was calculated to be $2.3 \times 10^{18}$ cm$^2$. Assuming a filling factor of unity, the resulting flux of non-thermal electrons was calculated to be $\geq 4 \times 10^{39}$ ergs cm$^{-2}$ s$^{-1}$. The bottom panel of Figure 3 shows the corresponding velocity maps in the He I and Fe XIX lines. The He I map shows consistent downflows of 20–50 km s$^{-1}$ until the slit leaves the flaring region at $\sim 12:50$ UT. A velocity map in O V showed a similar trend. However, the Fe XIX map shows strong upflows of $190$–$280$ km s$^{-1}$ during the HXR peak. Again, no significant flows were in observed in Mg X or Fe XVI. (See Milligan et al. 2006a.)

4. DISCUSSION AND CONCLUSION

Simultaneous X-ray and EUV observations of chromospheric evaporation during the impulsive phase of two solar flares are presented using data from RHESSI and SOHO/CDS. Here we report observational evidence for both gentle and explosive evaporation due to nonthermal
Figure 4. Plasma velocity as a function of temperature for each of the five lines observed using CDS during the two events. Positive velocities indicate downflows, while negative values indicate upflows. The data points plotted with filled circles denote the values obtained for the C9.1 flare (gentle evaporation), while the open triangles illustrate the values found for the M2.2 flare (explosive evaporation). The dotted and dashed lines connecting the points are added to guide the reader.

As a consequence, our findings support the theoretical models that predict that the response of the solar chromosphere is sensitively dependent on the flux of accelerated nonthermal electrons. Our results also support the prediction that a threshold value for the nonthermal electron flux exists above which the chromosphere cannot efficiently radiate the deposited energy. Fisher, Canfield, & McClymont (1985a) proposed that this threshold value is $\sim 3 \times 10^{10}$ erg cm$^{-2}$ s$^{-1}$. Above this value, electron fluxes were shown to begin to drive chromospheric condensation, a process resulting from the high pressures reached by the rapidly expanding evaporated material.

The recent hydrodynamic simulations of Abbott & Hawley (1999) and Allred et al. (2005) have been developed to include more realistic electron beam parameters and a non-LTE treatment of the solar atmosphere. These more detailed calculations still provide the distinction between gentle and explosive evaporation for differing nonthermal electron fluxes. These models will be further developed to include higher temperature plasmas that will be observed by the EUV Imaging Spectrometer (EIS) on board Solar-B, due for launch in late 2006. By combining EIS observations with RH E S S I data in the future, an even greater understanding on the behaviour of high-temperature plasmas during solar flares will be achieved.

ACKNOWLEDGMENTS

This work has been supported by a Department of Employment and Learning studentship in conjunction with a Cooperative Award in Science and Technology from NASA Goddard Space Flight Center. We would like to thank Brian Dennis and the RHESSI team, Joe Gurman, and Dominic Zarro at Goddard for their continued support. SOHO is a project of international collaboration between the European Space Agency and NASA.

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