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FAR UV SPECTRA OF THE CORONAL MASS EJECTION ASSOCIATED WITH THE 2002 21 APRIL X-CLASS FLARE

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ABSTRACT

The X-class solar flare on 2002 21 April was observed with many instruments, and it produced a very fast Coronal Mass Ejection (CME). We present observations of the CME made with the UltraViolet Coronagraph Spectrometer (UVCS). The spectra provide physical parameters of the pre-CME streamer and Doppler velocities during the streamer blowout. The blowout appears as a rapid fading of the O VI emission at zero velocity and the rapid acceleration of sheets of gas to 800 km s^{-1}. A small, transient brightening in the [Fe XVIII] λ974 line shows rapidly moving hot plasma, perhaps related to reconnection heating associated with ejection of the CME. Observations of a remarkably similar CME observed on 2002 23 August are included for comparison.

Subject headings: solar wind– Sun:activity–Sun:corona–Sun:coronal mass ejections (CMEs)

1. INTRODUCTION

The X1.5-class flare on 2002 21 April is among the best-observed events in recent history. Thanks to the Max Millenium campaign to obtain coordinated observations with many instruments, EUV images and spectra from the *SOHO* and *TRACE* satellites along with numerous ground-based radio and optical observations complement the hard X-ray images and spectra from the *RHESSI* satellite. As the first X-class flare that *RHESSI* observed, and an event detected by the *TIMED* satellite as well, the April 21 flare is especially important. Preliminary analyses of SUMER observations have been presented by (6),and (5) discuss *RHESSI* observations of gamma rays produced by impact of energetic particles from this flare on the Earth's atmosphere.

The 2002 21 April flare occurred at the W limb near latitude -12°, beginning to rise at 00:40 UT and peaking at 01:40 UT in GOES hard X-ray flux. It produced a fast, powerful Coronal Mass Ejection (CME). Coronagraph images from the Large-Angle Spectroscopic Coronagraph (LASCO) indicate a speed above 2000 km s^{-1}, and effects of the CME were felt near the Earth. On 2002 23 August another CME occurred at the W limb. The flare region was behind the limb, but bright loops appeared above the limb in the Extreme Ultraviolet Imaging Telescope (EIT) 195Å image at 01:15 UT. Again, LASCO images indicate a speed of roughly 2000 km s^{-1}.

This paper presents ultraviolet spectra of the 21 April CME obtained with the UltraViolet Coronagraph Spectrometer (UVCS) aboard the SOHO satellite. We derive the physical characteristics of the pre-CME streamer and study its violent disruption. A transient feature seen in the high temperature emission line of [Fe XVIII] may be the signature of the reconnection current sheet that appears beneath the rope of twisted magnetic flux in some CME models. The manifestation of the 2002 23 August event at 1.6 $R_\odot$ was remarkably similar, and we present spectra of that event for comparison. The characteristics of these events may be typical manifestations of very fast CMEs associated with X-class flares.

2. OBSERVATIONS

21 April: As part of the Max Millenium campaigns, the UVCS instrument ((Kohl et al. 1995)) was pointed above Active Region NOAA AR 9906 at a height of 1.53 $R_\odot$ from Sun center and a position angle of 262°. A series of 120 second exposures lasting until 01:55 UT covered the wavelength intervals 942-964, 966-980, 990-994, 997-1008 and 1023-1042 Å. The Si XII $\lambda\lambda$499, 521 doublet is detected in second order. The 100 μ slitwidth delivers a resolution of 0.4 Å. In order to maximize spectral coverage within telemetry limitations, the 990-994 and 942-964 Å panels were binned onboard to 0.3 Å, while the other panels were binned to 0.2 Å. The data were binned to 42″ along the spatial direction. The data calibration is described by Gardner et al. (2002).

23 August: The same observing sequence and instrument parameters were employed. The target was AR 0069, the subject of a major flare watch until it rotated past the limb, at a position angle of 260°. The observations continued until 06:49 UT.

3. ANALYSIS

3.1. *Streamer Parameters*

Figure 1a shows the intensities in various emission lines along the UVCS slit before the 21 April event. The O VI lines show peaks at -8′ and +2′ along the slit relative to slit center at PA=262°, while Lyβ shows a single broad peak. The peak in Si XII between about -3′ and -5′ suggests that this is partially due to a higher temperature in the center of the broad streamer apparent in Lyβ. However, the dip in both O VI and Si XII between -1′ and +1′ cannot be accounted for by temperature alone. It resembles the structure of a quiescent equatorial streamer observed near solar minimum, though the dip in the equatorial streamer is much broader. That structure was interpreted in terms of a closed magnetic field core with depleted abundances surrounded by open field legs having more normal abundances (Raymond et al., 1997). The variation in O VI/Lyβ suggests a factor of 1.6 change in the oxygen abundance between the minimum and maxima of the O VI intensity. The line of sight quite probably passes through the legs of the streamer even near the O VI minimum, so 1.6 is a lower limit to the contrast in abundances.

Figure 1b shows the intensity profiles on 23 August before (50 exposures between 22:27 UT Aug. 22 and 00:16 UT Aug. 23) and after (02:28-04:15 UT) the event. (The April 21 event was similar, but the observing sequence ended before a definitive "after" state was reached.) The other spectral lines resembled those of 21 April in that Lyβ showed a broad peak centered on the O VI minimum, and faint [Fe XVIII] λ974 peaked in the region of the higher O VI peak. In this streamer, the dip in O VI coincides with a broad peak in Si XII and a drop in [Si VIII], indicating that in this case the O VI dip results mostly from high temperature.

Both streamers are relatively hot compared with other streamers at this height, in that the [Fe XVIII] λ974 line is detectable, though faint. This line is seldom detected at 1.5 $R_\odot$, though it is was seen in the streamer above an exceptionally energetic active region ((Ciaravella et al. 2002); (Ko et al. 2002a)). The temperature structure can be derived from the intensities of the lines of H I, O VI, [Si VIII], [Si IX], Si XII, [Fe X], [Fe XIII] and [Fe XVIII] in our spectral windows. For the 21 April case, a flat differential emission measure distribution covering log T = 6.0 to 6.4, with DEM=3×10^{24} cm^{-5} in each interval of 0.1 in log T matches the line intensities. The 23 August streamer has a similar emission measure, but the temperature range is shifted toward higher temperatures by about 0.1 in log T.

The density of the streamer can be derived from the ratio of the O VI lines at $\lambda\lambda$1032, 1037 by computing the collisionally excited and radiatively excited contributions to their intensities ((4); (Raymond et al. 1997)). The density falls in the range 2 to 3×10^7 cm^{-3} in the bright section of the streamer. As with the temperature, this density is comparable to that at the same height in an unusually hot, bright streamer ((Ciaravella et al. 2002); (Ko et al. 2002a)). Given that density, the line intensities imply a depth along the line of sight of about 1 $R_\odot$, comparable to the width of the bright streamer along the slit. At the height of the LASCO C2 image, only a very narrow streamer stalk is visible. In the standard picture of helmet streamers, this is the extension of the open field regions corresponding to the UVCS O VI peaks.

3.2. *Streamer Blowout*

Figure 2 shows the spectral region near the O VI λ1032 emission lines at six times; just before the eruption and at 5 times over the following 15 minutes. The region near the slit center is the first to be affected, as emission at line center dims and strongly red-shifted and blue-shifted components appear. The disturbance spreads rapidly along the slit, and Doppler shifts reach +500 and -850 km s^{-1} in the 21 April event, or -500 and +810 km s^{-1} on 23 August. On 21 April on the red side, the Doppler shift peaks about 7 minutes after the red-shifted component appears, then declines to roughly +150 km s^{-1}. On the blue side, the Doppler shifts seem to reach asymptotic speed of 750 to 850 km s^{-1}, and the emission simply fades away. The fact that blue-shifts are larger than red-shifts on 21 April implies a skewness towards the Earth, perhaps related to strength of the observed near-Earth effects.

The long slit spectra in Figure 2, particularly the spectrally narrow red- and blue-shifted peaks, imply that the O VI emitting gas is concentrated in relatively thin sheets. These are presumably the streamer legs seen as the brightness peaks in the intensity distribution along the slit. The dimming at line center corresponds to displacement of the streamer by either the oxygen-depleted closed field core or the low density CME void. For about the first 500 seconds, the disturbance spreads along the slit at a rate of about 1000 km s^{-1} in each direction, about half the speed of the CME front. This is a little larger than the Doppler shift velocities, suggesting that the structure is not quite cylindrically symmetric. However, the outer edges of the LASCO bubble are somewhat fainter, and may not be visible in the UVCS spectra. A slab of the corona having the density derived above that is 0.25 $R_\odot$ thick with lateral dimensions equal to the UVCS slit length would weigh about 10^{16} grams, or a typical CME mass. Thus the disrupted streamer accounts for much of the CME mass.

The generally narrow O VI profiles also indicate that O VI is not heated to high temperatures, as has been observed in CME-driven shocks (Raymond et al. 2000; Mancuso et al. 2002). The apparent lack of a shock suggests a fast mode speed faster than the CME speed. With the density derived above, this requires $B \geq 4$ Gauss.

3.3. *Hot Plasmoid or Current Sheet?*

These events are unusual among the CMEs observed by UVCS in that they show transient features in the [Fe XVIII] line at 974 Å. UVCS spectra of some events show bright, narrow [Fe XVIII] emission features that last many hours ((Ciaravella et al. 2002); (Ko et al. 2002b)). These are identified with the current sheets predicted by many flux rope models of CMEs (e.g. (Lin & Forbes 2000); (Amari et al. 1999); (Manchester 2001)). In the April and August events, we see clouds of [Fe XVIII] emitting gas smaller than the sizes of the disrupted streamers. They extend along the slit about 2$'$ and 7$'$ (April and August, respectively), in both cases about the same extent as the fainter [Fe XVIII] emission in the pre-CME streamer. In both cases the enhanced [Fe XVIII] emission lasts only about 8 minutes. However, if these features correspond to plasmoids moving across the slit at the speeds of the CME leading edges, their durations require lengths of about 7×10^{10} cm.

Figure 4 shows the intensities of several lines extracted from slit positions -84$''$ to +84$''$ along the UVCS slit on 21 April. The plot for 23 August shows very similar time profiles, but with Si XII about twice as bright and the other lines about half as bright as on 21 April. The O VI and Si XII intensities begin to fade at 01:06 UT when the CME removes streamer material from the line of sight. The transient feature appears at 01:16 UT, reaching 0.4, 7.0 and 2.7×10^9 photons cm^{-2} s^{-1} sr^{-1} in Lyβ, Si XII and [Fe XVIII], respectively. For solar photospheric abundances and ionization equilibrium, the line ratios imply $6.7 \leq \log T \leq 6.9$ and an emission measure of 2×10^{25} cm^{-5} according to the predictions of the the CHIANTI ((Dere et al. 2001)) database. If the structure is more or less cylindrical, the emission measure and transverse scale imply a density near 5×10^{7} cm^{-3}. If it corresponds to a sheet of gas seen edge-on, the density could be smaller. On the other hand, the emitting gas might occupy a small fraction of the apparent volume, implying a higher density.

The nature of the hot transients is difficult to ascertain. Their occurance during the Doppler splitting of the O VI lines suggests a position neither ahead of the main CME void, as might be expected in the breakout model (1), nor as a current sheet trailing the flux rope, as predicted in the Lin & Forbes (2000) and inverse polarity flux rope models (3). The most interesting possibility within the context of current CME models is that the [Fe XVIII] comes from the region where plasma accelerated in the current sheet encounters the trailing edge of the flux rope. The plasma is expected to be moving at a few hundred km s^{-1} relative to the CME structure, and it is compressed and heated when it encounters an obstacle. However, our diagnostic information for this event is fragmentary, and we cannot be sure that the hot plasma is related to reconnection in the flare and CME events at all. A plasmoid of hot active region material could have been ejected without significant heating beyond active region temperatures. While it would cool rapidly due to expansion, the recombination time scale is 1000 seconds at 3×10^{7} cm^{-3}. Thus the gas could be cooler when it was observed by UVCS than indicated by its ionization state.

4. DISCUSSION

The April event is associated with an X-class flare, and the August event is likely to be associated with a strong flare behind the limb, as indicated by post-CME loops above the limb in EIT images. A CME associated with an X-Class flare on 2002 21 July, also as part of the Max Millenium campaign, was quite similar in both the evolution of the O VI profiles and the presence of a transient feature in [Fe XVIII], though the July event was fainter, and the O VI evolution was faster. All three events are unusual among CMEs studied so far by UVCS in that they show very high ionization and no evidence for cool prominence material. The existence of a substantial amount of highly ionized gas corresponds well to measurements of the ionization state of ICMEs measured *in situ* ((2)). While 3 events do not give much of a sample, it seems that X-class flares are associated with very fast CMEs which contain little cool filament material.

The O VI lines provide a clear look at streamer disruption in 3D, with line-of-sight speed comparable to the speed at which the disturbance moves along the slit, both speeds about 1/2 the speed of the CME leading edge in the plane of the sky. The temperature, density and ionization state of the pre-CME streamers are similar to those observed above hot, bright active regions. The streamer masses are comparable to typical CME masses, so the pre-CME conditions provide a useful comparison for *in situ* measurements of these quantities in the CMEs and in the associated energetic particles. However, it appears that the shock had not formed at 1.5 $R_{\odot}$due to a fairly strong magnetic field.

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Figure Captions

Figure 1a. Intensities of the Lyβ, O VI, Si XIII and [Fe XVIII] lines along the UVCS slit shortly before the 2002 21 April event. b) The O VI λ 1032 intensities along the slit before and after the 2002 23 August event.

Figure 2. Six longslit spectra for each event showing the O VI $\lambda\lambda$1032, 1038 lines, with Lyβ and the second order Si XII λ521 lines faintly visible. Velocities corresponding to Doppler shifts of O VI λ1032 are shown on the horizontal scales, and UT times for each exposure are shown to the left and right.

Figure 3. Evolution of the intensities of several spectral lines with time extracted from a small ($210''$) section of the UVCS slit centered on the bright transient [Fe XVIII] feature.

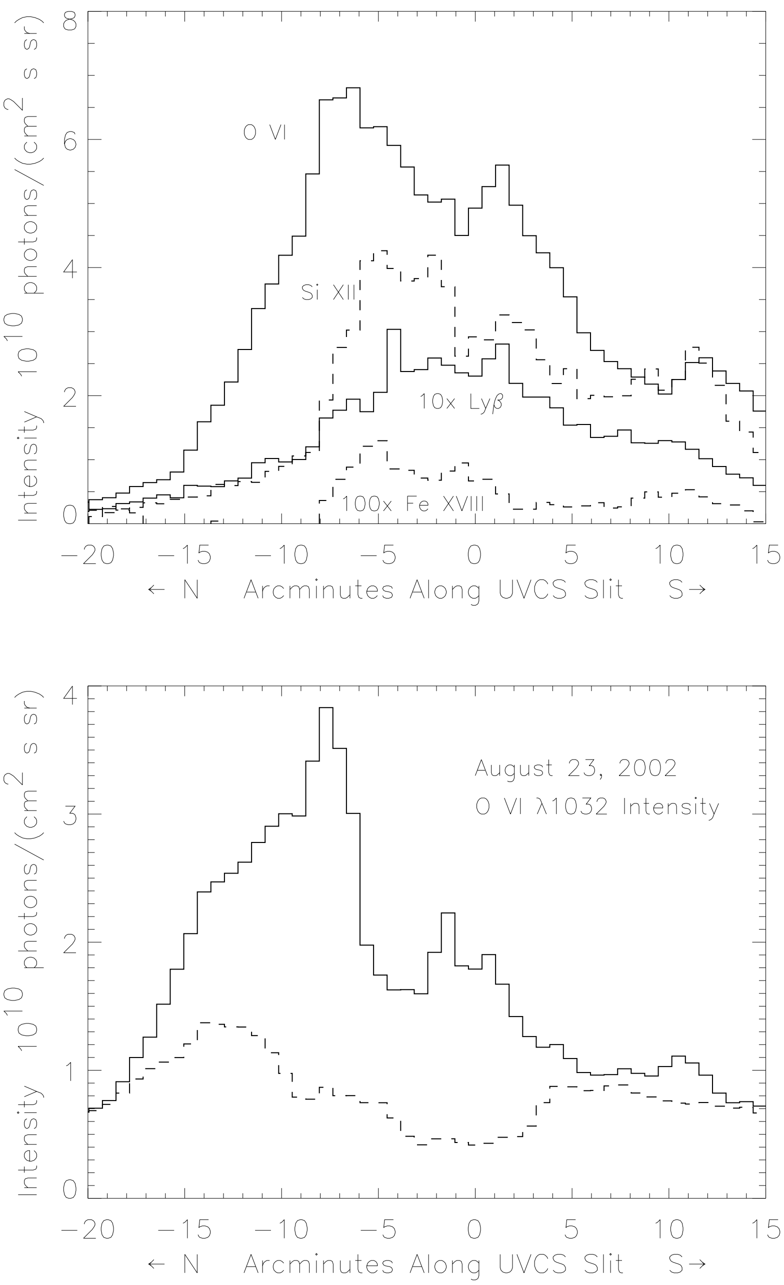
O VI
Si XII
10x Lyβ
100x Fe XVIII
Intensity 10^{10} photons/(cm^2 s sr)
← N Arcminutes Along UVCS Slit S→
August 23, 2002
O VI λ1032 Intensity

Figure 1.

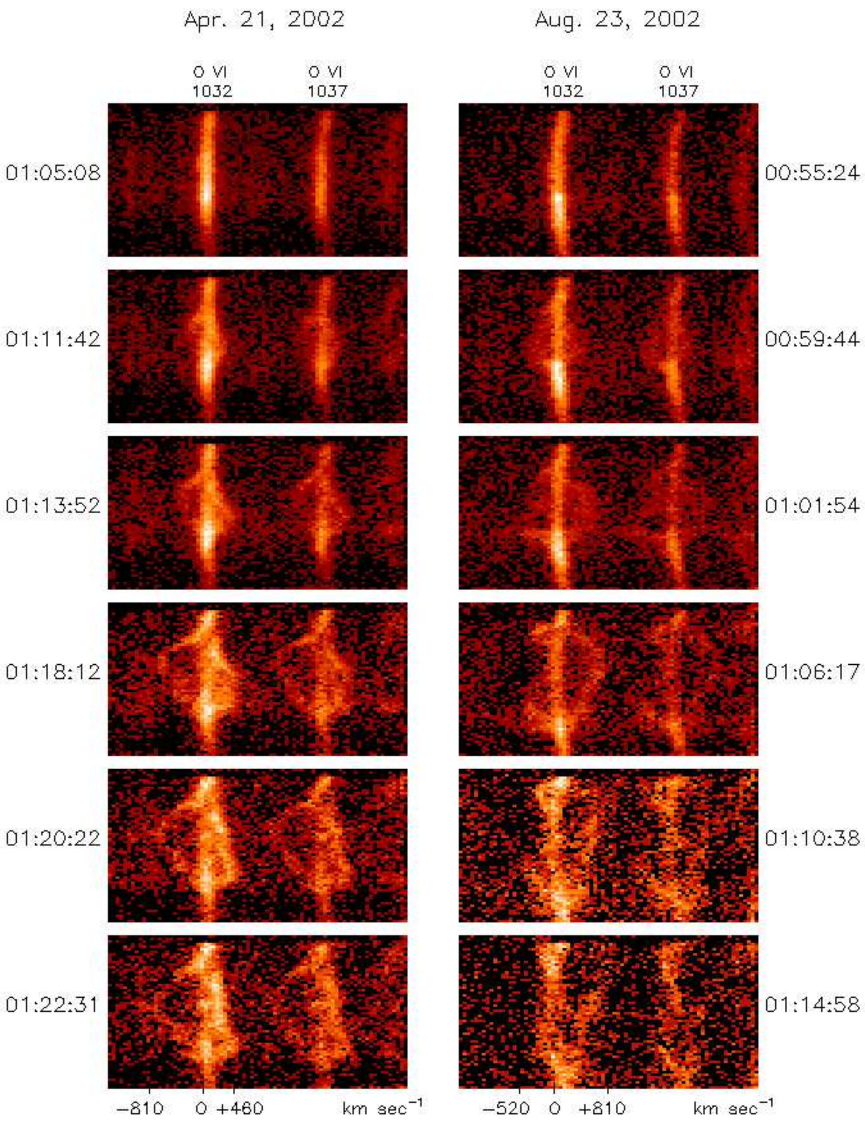
Apr. 21, 2002
Aug. 23, 2002
O VI 1032
O VI 1037
O VI 1032
O VI 1037
01:05:08
01:11:42
01:13:52
01:18:12
01:20:22
01:22:31
00:55:24
00:59:44
01:01:54
01:06:17
01:10:38
01:14:58
−810 0 +460 km sec−1
−520 0 +810 km sec−1

Figure 2.

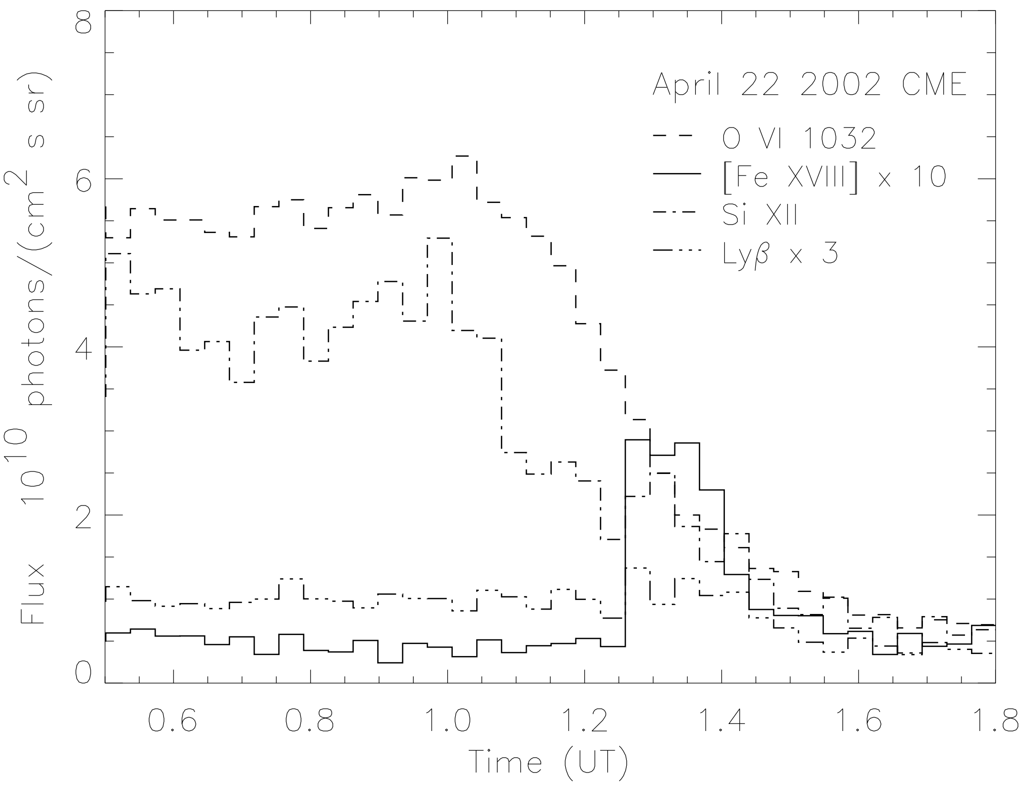
April 22 2002 CME
O VI 1032
[Fe XVIII] x 10
Si XII
Lyβ x 3
Flux 10^{10} photons/(cm^2 s sr)
Time (UT)
0
2
4
6
8
0.6
0.8
1.0
1.2
1.4
1.6
1.8

Figure 3.