OBSERVATION OF UPLIFTS DURING SOFT X-RAY SOLAR FLARES

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ABSTRACT

Upflows of the soft X-ray emission regions of four flares located near Sun center have been determined from the blueshift of the absolute wavelength of the Ca xix resonance lines recorded by the SOLFLEX spectrometer on the P-78 spacecraft. Peak upward velocities were 35–90 km s\(^{-1}\) and occurred during the time of gradual increase in the Ca xix count rate and prior to the peak Hz emission. Rises in altitude of 7000–80,000 km were inferred from the upward velocities.

Subject headings: Sun: flares — Sun: X-rays

1. INTRODUCTION

The motions of the soft X-ray emission regions of solar flares have been determined from the Doppler shift and broadening of the Ca xix emission near 3.18 Â that was recorded by the SOLFLEX Bragg crystal spectrometer on the P-78 spacecraft. Doschek et al. (1980) measured line broadening soon after flare onset and inferred random velocities of 130 km s\(^{-1}\). Feldman et al. (1980b) observed features on the blue wing of the Ca xix resonance line and inferred Doppler motions of 400 km s\(^{-1}\). Upflows of 250–400 km s\(^{-1}\) were also observed by Karpen, Doschek, & Seely (1986) and by Doschek et al. (1989). Based on spectra recorded by the bent crystal spectrometer (BCS) on the Solar Maximum Mission spacecraft, upflows of comparable velocities were determined by Antonucci et al. (1982), Antonucci & Dennis (1983), and Antonucci et al. (1985). Numerical modeling of chromospheric evaporation, in which upflowing plasma is assumed to rapidly fill magnetic flux tubes, predicted velocities as high as 600 km s\(^{-1}\) (Fisher, Canfield, & McClymont 1985; Mariska, Emslie, & Li 1989). In contrast, McClements & Alexander (1989) analyzed nine flares near Sun center that were observed by BCS and found no evidence for Ca xix wavelength shifts exceeding 1 mÅ (Doppler velocity of 100 km s\(^{-1}\)).

In this paper, we analyze four flares near Sun center that were observed by SOLFLEX. The characteristics of the SOLFLEX spectrometer make it possible to reliably detect Doppler velocities as small as 7 km s\(^{-1}\). The absolute wavelengths of the Ca xix resonance lines were found to be blueshifted soon after flare onset, and upflows as high as 35–90 km s\(^{-1}\) are determined. These results are compared to previous results, and the implications for the chromospheric evaporation model are discussed.

The X-ray spectra were recorded by the Naval Research Laboratory Bragg crystal spectrometer (SOLFLEX) that was flown on the Air Force P78-1 spacecraft (Feldman, Doschek, & Kreplin 1980a). This instrument recorded the resonance lines and the nearby dielectronic satellite lines of Ca xix (3.18 Â), Ca xx (3.02 Å), Fe xxv (1.85 Å), and Mg xii (8.42 Å). The four crystals were mounted on a common shaft that rotated in steps of 20° and at the rate of 8 steps s\(^{-1}\). The spectra were scanned in 450 steps from short wavelength to long wavelength and then in 450 steps from long wavelength to short wavelength over the same wavelength range. The instrument observed the entire solar disk and recorded spectra continuously except when the spacecraft was performing other functions or when the spacecraft was on the dark side of the Earth. The stability of the spacecraft pointing was better than 1", much smaller than the crystal rotational step of 20°.

Typical Ca xix scans are shown in Figure 1, where the labeling of the Ca xix resonance line (w) and the other nearby transitions follow the convention of Gabriel (1972). The wavelengths, intensities, line profiles, and blending of these features in the SOLFLEX spectra are well understood (Seely & Doschek 1989). The primary observable in this work is the separation (in steps) between the two resonance lines w (see Fig. 1). In general, the separation changes soon after flare onset and approaches a constant value in the late decay phase. The origin of the change in separation is twofold. First, a change in the relative velocities of the spacecraft and the emitting plasma along the line of sight results in a change in the separation. Second, a movement of the plasma perpendicular to the line of sight and along the crystal dispersion direction (or a change in the spacecraft pointing) results in a change in the separation. The second effect is dominant for limb flares, where the bulk plasma tends to rise vertically along a solar radius into the corona and perpendicular to the line of sight. The observation of the second effect and the determination of the rise in altitude of limb flares were originally reported by Seely & Feldman (1984). This technique was also used to determine the rise in altitude of a long-duration limb flare that was associated with a coronal mass ejection (Kreplin et al. 1985). The first effect (Doppler shift) is dominant for flares near Sun center, where the bulk plasma motion is primarily along the line of sight, and the study of flares near Sun center is the subject of this paper.

As discussed by Seely & Feldman (1984), a computer program identified the data points that exceeded the average count rate in the neighborhood of the Ca xix resonance line by 2 standard deviations. Typically, about 10 data points near the peak of the line were so identified. The computer program then weighted the data points by their count rates and calculated the step number of the line centroid. This was done for each of the two Ca xix resonance lines in a pair of spectra, and the separation between the two resonance lines was used to calculate the line shift. Since each pair of spectra was scanned in 900 steps and since the data were recorded continuously, the calculated distance between adjacent pairs of spectra in the data.
stream should ideally be equal to 900 steps. Depending on the count rate at the resonance line and on the background noise level, the calculated distances between adjacent pairs of spectra differed from 900 steps by 0.01–0.03 steps, and this is an indication of the precision of the determination of the separation between the two Ca xix resonance lines.

The change in separation was found to be qualitatively different for flares near a solar limb and near Sun center. For flares near the west (east) limb, the separation initially increased (decreased) and then after tens of minutes approached values that were considerably different from the initial values (see Fig. 2). This was interpreted as an increase in the altitude of the emission region of limb flares (Seely & Feldman 1984). The change in separation for two flares near Sun center is shown in Figure 3. In contrast to the limb flares, for these two flares near Sun center the separation initially increased, reached a maximum after approximately 5 minutes, and then decreased toward the initial separation values. This is interpreted as a blueshift resulting primarily from the upward velocity of the bulk plasma.

2. FLARE GEOMETRY

In order to understand the geometry of the flare plasma motion and the spacecraft pointing, let us consider a flare emission region at solar latitude $\phi$ and longitude $\theta$ as shown in Figure 4a. The flare position projected onto the plane of the solar disk is

$$E_s = R \sin \phi$$
$$A_s = R \cos \phi \sin \theta$$

where $R$ is the solar radius. Note that the signs of $E_s$ and $A_s$ are defined such that $E_s > 0$ for $\phi > 0$ (north latitude) and $A_s > 0$ for $\theta > 0$ (west longitude). The spacecraft roll angle $\beta$ is measured from solar north as shown in Figure 4b, where $z$ is the crystal dispersion axis projected onto the solar disk. The flare positions parallel and perpendicular to this axis are given by $E$ and $A$, respectively, where

$$R \sin \phi = A \sin \beta + E \cos \beta$$
$$R \cos \phi \sin \theta = A \cos \beta - E \sin \beta$$

Solving for $E$ and $A$,

$$E = R \sin \phi \cos \beta - R \cos \phi \sin \theta \sin \beta$$
$$A = R \sin \phi \sin \beta + R \cos \phi \sin \theta \cos \beta$$

The sign of $E$ is such that $E > 0$ in the $+z$ direction.

The spacecraft pointing coordinates are the angles $\epsilon$ and $\alpha$ from Sun center and in the directions parallel and perpendicular to the dispersion axis $z$, respectively. The distances project-
Fig. 4.—(a) The solar latitude \( \phi \) and longitude \( \theta \). (b) The crystal dispersion axis \( z \) projected onto the plane of the Sun and the spacecraft roll angle \( \beta \). \( E \) and \( A \) are the flare positions parallel and perpendicular to the dispersion axis, respectively.

The absolute value of the separation between the two resonance lines \( w \) is determined primarily by the offset between the flare and spacecraft pointing coordinates along the dispersion axis. Shown in Fig. 5 are the observed absolute separations between the Ca xix and Fe xxv resonance lines as functions of the spacecraft-flare offset in units of the solar radius. For each flare, the offset was derived from the spacecraft pointing coordinates at the time the initial X-ray spectra were recorded and the coordinates of the H\( \alpha \) flare listed in Solar-Geophysical Data. For example, the data point near offset \(-2\) is a flare near the east limb \( (\theta = -89^\circ, \phi = 10^\circ \) on 1981 August 3) recorded when the spacecraft was pointed near the west limb \( (\Theta = 66^\circ, \Phi = -13^\circ, \beta = 72^\circ) \). The straight lines in Figure 5 are least-squares fits to the data points. Deviations from these straight lines are attributed to the difference in the positions along the dispersion axis of the X-ray and H\( \alpha \) flares, the uncertainties \(<1^\prime\) in the absolute values of the spacecraft pointing angles \( \epsilon \) and \( \alpha \), and the uncertainty in the solar coordinates of the H\( \alpha \) flare which can be several degrees of longitude and latitude.

### 3. EFFECTIVE WAVELENGTH SHIFT

Spectral scans such as shown in Figure 1 were recorded every 1.88 minutes. The separation between the two resonance lines \( w \) was measured for each scan. Also measured was the separation between the last line \( w \) of a given scan and the first line \( w \) of the next scan. Thus values of separation were obtained every 0.94 minutes.

For Ca xix, a change in separation of one step \( (20^\prime) \) corresponded to an apparent shift in the effective wavelength of the resonance line \( w \) of 0.235 m\( \text{\AA} \). For a flare at Sun center, this resulted primarily from a change in velocity of 22 km s\(^{-1}\) along
the line of sight. For a limb flare, this shift resulted primarily from a rise in altitude of 7250 km along the dispersion axis. As mentioned above, the precision of the measurement of the separation was typically 0.01–0.3 steps, an corresponded to a precision of better than 6 km s\(^{-1}\) in velocity or 2000 km in altitude.

In general, for fixed spacecraft pointing, changes in the separation between the resonance lines \(w\) can result from the movement of the emitting plasma along the dispersion axis, the movement of the plasma parallel to the line of sight, and the movement of the spacecraft along the line of sight. The first effect causes an effective wavelength shift of

\[
\delta \lambda_d = (h_d/R_e)2d \cos \gamma,
\]

where \(d\) is the crystal lattice spacing (4.00 Å for the Ca xix lines), \(R_e\) is the Earth-Sun distance, \(\gamma\) is the Bragg angle, and \(h_d\) is the distance that the plasma moves projected onto the dispersion axis. Referring to Figure 6,

\[
h_d = h(-\cos \phi \sin \theta \sin \beta + \sin \phi \cos \beta),
\]

where \(h\) is the vertical rise in altitude along a solar radius (\(h > 0\) if ascending).

The bulk motion of the plasma toward the spacecraft results in the Doppler shift in wavelength

\[
\delta \lambda_w = -\lambda_{0w} \delta v \cos \theta \cos \phi /c,
\]

where \(\delta v\) is the change in velocity in the vertical direction along a solar radius (\(\delta v > 0\) for upflow). The Doppler shift resulting from the spacecraft orbital motion is

\[
\delta \lambda_s = -\lambda_{0s} \delta v_0 /c,
\]

where the speed of the spacecraft (which was in polar orbit) was \(\delta v_0 = 7.2\) km s\(^{-1}\) at the beginning of the spacecraft day and \(\delta v_0 = -7.2\) km s\(^{-1}\) at the end of the spacecraft day. The total effective shift in wavelength is

\[
\delta \lambda = \delta \lambda_d + \delta \lambda_w + \delta \lambda_s.
\]

Solving equation (13) for \(\delta v\),

\[
\delta v = (c/\lambda_{0w}f_1)(-\delta \lambda - \delta v_0 \lambda_{0w} /c + hf_2 2d \cos \gamma /R_e),
\]

where the geometrical factors are

\[
f_1 = \cos \theta \cos \phi,
\]

\[
f_2 = -\cos \phi \sin \theta \sin \beta + \sin \phi \cos \beta.
\]

For the case of flares near Sun center (\(\phi = 0, \theta = 0\)), the factor \(f_2\) is small. As a first approximation, we neglected the last term in equation (14) and determined \(\delta v\). Using these values of \(\delta v\), the change in altitude \(h\) was calculated for each time interval, and these values of \(h\) were used in equation (14) to obtain improved values of \(\delta v\). These corrections were small for the flares near Sun center that were selected for study. The improved values of \(\delta v\) were then used to obtain improved values of \(h\).

4. RESULTS

The results for four flares near Sun center are presented in Figures 7–10. These figures show the counts at the peak of the resonance line \(w\) and the bulk plasma velocity and altitude in the vertical direction along a solar radius. The initially obtained values of velocity and altitude are shown by the dashed curves and the open data symbols, and the improved values of velocity and altitude are shown by the solid curves and the filled data symbols. The velocities are normalized to zero near the end of the observed data, and the altitudes are normalized to zero at the beginning of the observed data. The times of the peak Hα emission are also indicated.

Shown in Figure 7 are the results for the flare of 1979 November 9. The Hα flare was observed at solar coordinates S15W00 beginning at 03h04m, peaking at 03h06m, and ending at 03h18m. The maximum upward velocity, derived from the Ca xix spectra, was 80 km s\(^{-1}\) and occurred during the time of gradual increase in the Ca xix count rate and 1 minute prior to the peak Hα emission. The rapid upflow lasted for 2 minutes, and the plasma reached an altitude of 7000 km. There is evidence for downward flow at the beginning of the flare, but the velocity is only -15 km s\(^{-1}\), and this was the only flare for which such downflow was observed.

The results for the 1980 December 16 flare are shown in Figure 8. The Hα flare was observed at N12E20 beginning at 11h49m, peaking at 11h54m, and ending at 12h36m. The maximum upward velocity was 80 km s\(^{-1}\) and occurred during the time of gradual increase in the Ca xix count rate and a few minutes prior to the peak Hα emission. The altitude exceeded 80,000 km.

Shown in Figure 9 are the results for the flare of 1980 May 18. The Hα flare was observed at N16E19 beginning at 01h03m, peaking at 01h08m, and ending at 01h27m. The upward velocity was 35 km s\(^{-1}\) at the beginning of the Ca xix emission and decreased over the next 4 minutes. The increase in altitude during this time was 7000 km.

The results for the 1979 March 22 flare are shown in Figure 10. The Hα flare was observed at N07W19 beginning at 03h24m, peaking at 03h25m, and ending at 03h55m. For this flare, the separation of both the Ca xix and Mg xii resonance lines could be determined for the duration of the flare. The upward velocities of the Ca xix and Mg xii emission regions exceeded 90 km s\(^{-1}\) early in the flare (prior to peak Hα emission), and the maximum altitudes of both regions were approximately 10,000 km. There is evidence that the altitudes decreased late in the flare, although the corrections for plasma motion along the dispersion axis are rather large for this flare.
Fig. 7.—The results for the 1979 November 9 flare observed at S15W00 as functions of time after 03:00 UT. (a) shows the counts at the peak of the Ca xix resonance line, (b) the velocity derived from the change in separation between the Ca xix resonance lines, and (c) is the altitude derived from the velocity. The velocity is normalized to zero late in the flare, and the altitude is normalized to zero at the time of first observation. In (b) and (c), the dashed curves and open data symbols indicate the initially obtained values of velocity and altitude, and the solid curves and filled data symbols indicate the improved values of velocity and altitude. The time of the peak Hz emission is indicated by the arrow in (b).

Fig. 8.—The results for the 1980 December 16 flare observed at N12E20 as functions of time after 11:00 UT. See legend for Fig. 7.

Fig. 9.—The results for the 1980 May 18 flare observed at N16E19 as functions of time after 01:00 UT. See legend for Fig. 7.
The upward velocities of the bulk plasma emission regions of four flares near Sun center were determined from the soft X-ray spectra. In general, the peak velocities were in the range 35–90 km s\(^{-1}\) and were observed to occur during the time of gradual increase in the soft X-ray count rate and prior to the time of peak H\(\alpha\) emission. The upward velocities diminished in the decay phase. Increases in altitude of 7000–80,000 km were derived from the upward velocities. The bulk plasma emission regions tended to rise rapidly during the early phases of the flares and to stabilize or descend late in the flares. This is consistent with the view that an event early in the flare caused the plasma to rise, perhaps filling and stretching a magnetic field structure, and that the plasma late in the flare was confined by the magnetic field structure. The upward velocity and the final altitude attained can be used to infer the characteristics of the flare excitation event and the magnetic field structure.

These results may be compared with the results of McClements & Alexander (1989) who analyzed nine flares near Sun center and four flares near the west limb that were observed by the BCS spectrometer on SMM. The positions of the Ca xix spectra from the disk flares were determined relative to the positions of the Ca xix spectra from the west-limb flares with a precision of ±0.5 m (±50 km s\(^{-1}\)). It was concluded that there was no evidence for shifts exceeding 1 m (100 km s\(^{-1}\)). Since the peak velocities determined in the present work are in the range 35–90 km s\(^{-1}\), the present work is not inconsistent with the work of McClements & Alexander (1989).

As discussed in the Introduction, there is ample evidence that upflows as high as 400 km s\(^{-1}\) have been determined for some of the flares observed by the SOLFLEX and BCS spectrometers. The present work, and the work of McClements & Alexander (1989), indicate that such high velocities do not occur in all flares observed by these two spectrometers, at least during the times analyzed. Thus the high velocities predicted by the chromospheric evaporation model (up to 600 km s\(^{-1}\)) have not been observed to occur in all solar flares. This implies that, at the present time, the chromospheric evaporation model is not universally applicable to solar flares, and the application of this model to any particular flare is suspect.

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REFERENCES


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