DIRECT MEASUREMENT OF THE INCREASE IN ALTITUDE OF THE SOFT X-RAY EMISSION REGION DURING A SOLAR FLARE

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ABSTRACT

The upward motions of the hot thermal regions of several large (M type) solar flares have been determined from the soft X-ray spectral data recorded by the scanning spectrometer (SOLFLEX) on the P78-1 spacecraft. For the limb flares that are studied, the centroid of the Ca xix emission region moves to a higher altitude with an apparent speed of 20–40 km s⁻¹ for a period of 20–30 minutes following onset of the flare and reaches an altitude of 30,000–40,000 km. Although brief periods of downward motion of the emission centroid are observed, substantial decreases in altitude are not observed in any of the flares.

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

I. INTRODUCTION

In this Letter, we present a new technique for the determination of the upward motion of the soft X-ray emission region of solar flares. These results are important for the understanding of the production and dynamics of the hot (1.5 × 10⁷ K) thermal region of solar flares.

The motions of hot postflare loops were studied by Kahler (1977), MacCombie and Rust (1979), and Nolte et al. (1979) using images recorded by the X-ray telescope on Skylab. The upward motion of the soft X-ray emission region during the impulsive phase of disk flares was inferred from the blueshifted components of Ca xix spectral lines by Feldman et al. (1980). In data recorded by a rotating-crystal spectrometer, the change in position of the emission region of a limb flare results in a wavelength shift, and the present technique is based on the measurement of the apparent wavelength shift of the Ca xix resonance line.

The Naval Research Laboratory Bragg crystal spectrometer (SOLFLEX = solar flare X-rays) on the Air Force P78-1 spacecraft records the resonance and dielectronic satellite spectral lines of Ca xix (near 3.2 Å), Ca xx (3.0 Å), and Fe xxv (1.9 Å). The three crystals are mounted on a common shaft that rotates in steps of approximately 20° and at the rate of 8 steps s⁻¹. The spectra are scanned in 900 steps from short wavelength to long wavelength and then from long wavelength to short wavelength as shown in Figure 1. The data are recorded continuously except when the spacecraft is performing other functions or when the spacecraft is on the dark side of the Earth. A more complete description of the instrument is given by Feldman, Doschek, and Kreplin (1980).

As shown in Figure 2a, the rotating shaft is oriented nearly perpendicular to the ecliptic plane, and the detector is on the west side of the rotating shaft. The motion of the emission region parallel to the direction of dispersion results in an apparent shift in wavelength of the spectral lines. In practice, we measure the change in the separation of the two resonance lines which is equal to twice the wavelength shift of each resonance line (see Fig. 1). For an emission region on the solar limb, where the change in velocity along the line of sight is negligible, the change in separation between the Ca xix resonance lines is one step (0.235 mA) for each 7,250 km change in position along the direction of dispersion. For an emission region rising off the west (east) limb of the Sun, the wavelength shift is in the blue (red) direction.

II. DATA REDUCTION

For each pair of spectra (see Fig. 1), the separation between the Ca xix resonance lines is determined by the position of the emission region on the solar disk, the orientation of the spacecraft, and the relative motion of the plasma and the spacecraft. While it is possible to determine the absolute position of the emission region along the direction of dispersion, the accuracy of this measurement is only about 1° (44,000 km) because of the uncertainty in the absolute orientation of the spacecraft. The precision of the line-of-sight pointing of the spacecraft is better than 1", and as discussed below, the precision of the measurement of the change in altitude during the observation time is better than 2200 km.

Referring to Figure 2b, let us consider a flare at longitude θ and latitude φ. We assume that the soft X-ray emission region changes position by a vertical distance h (h > 0 if the emission region is ascending, h < 0 if descending). The distance projected onto the plane of the solar disk is hₚ as shown in Figure 2b. The distance projected onto the direction of dispersion at an angle β from the north pole is hₜ:

\[ hₜ = h (\cos \phi - \cos \sin \theta \sin \beta + \sin \phi \cos \beta). \]  

(1)

This change in position subtends an arc equal to hₜ/R at the Earth (R = 1 AU) and results in a wavelength shift of

\[ \delta \lambda = 2d\cos \gamma hₜ/R, \]  

(2)

where 2d cos γ = 2.428 Å.
Fig. 1.—The spectra of Ca xix from the 1981 August 3 flare at times (a) 20\textsuperscript{h} 24\textsuperscript{m}, (b) 20\textsuperscript{h} 40\textsuperscript{m}, and (c) 20\textsuperscript{h} 55\textsuperscript{m}. The resonance lines (w) and the strongest satellite lines are identified. The motion of the Ca xix emission region is determined from the change in separation between the Ca xix resonance lines. The separation between the resonance lines is measured from the centroids of the two line profiles, where the centroid is calculated by weighting the data points near the peak of the line according to the count rate.

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

\[ \delta \lambda_D = -\lambda_0 \delta v \cos \theta \cos \phi/c, \]  

where \( \delta v \) is the change in the speed of bulk motion along the direction \( h \) (\( \delta v > 0 \) for an increasing speed of ascent). Since the spacecraft is in a midday-midnight polar orbit, the speed of the spacecraft toward the Sun changes during the period of an orbit. The spacecraft approaches the Sun with a speed of 7.2 km s\(^{-1}\) at the beginning of the spacecraft day and recedes with a speed of \(-7.2\) km s\(^{-1}\) at the end of the spacecraft day.

The total wavelength shift is the sum of the spatial shift given by equation (2) and the Doppler shift due to the relative motion of the emission region and the spacecraft. Since each measurement of the change in wavelength separation of the resonance lines is related to two unknowns, the change in altitude \( h \) and the change in speed \( \delta v \) during the observation time, it is impossible to determine both unknowns without an auxiliary condition concerning \( h \) and \( \delta v \). At the solar limb, we assume that the bulk motion of the plasma is perpendicular to the line of sight (\( \delta v = 0 \)), and the observed wavelength shift is due to the change in height \( h \). At Sun center, we assume that the motion of the emission region is along the line of sight (\( h_d = 0 \)), and the wavelength shift is due to the change in velocity \( \delta v \). The motion of the spacecraft also contributes a small additional Doppler shift.

A computer program identifies the data points that exceed 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 are so identified. The computer program then weights the data points by their count rates and calculates the step number of the line center. This is done for each of the two Ca xix resonance lines in a pair of spectra (as shown in Fig. 1), and the separation between the two resonance lines is used to calculate the position of the Ca xix emission region. Since each pair of spectra is scanned in 900 steps and since the data are 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 distance between adjacent pairs of spectra differs from 900 steps by 0.01–0.3 steps. This corresponds to an uncertainty in the position of the Ca xix region of less than 2200 km.

We have analyzed four flares near Sun center and six flares near the limb that occurred during the years 1980 and 1981. For the four flares near Sun center, the Ca xix resonance line is blueshifted during the time of high emission, and this implies that the hot plasma is ascending. The three flares on the west limb indicate a blueshift, and the three flares on the east limb indicate a redshift. This is consistent with an increase in altitude of the emission region at the limbs. We report here the analysis of the Ca xix data for one flare on the west limb and one flare on the east limb. The analysis of the Ca xix, Ca xx, and Fe xxv data for a number of flares from the years 1979 through 1981 will be reported in a later publication.

III. 1981 AUGUST 3 FLARE

An Hα flare was observed on 1981 August 3 on the east limb at S10,E89 (φ = -10°, θ = -89° in our coordinate system). The Hα flare began at 20h19m, peaked at approximately 20h25m, and continued beyond 20h27m (Solar-Geophysical Data 1981). This flare was designated an M7.2 event. The count rate at the center of the Ca xix resonance line that was recorded by the P78-1 spacecraft is shown by the solid curve in Figure 3a. The Ca xix count rate peaked about 2 minutes after the Hα maximum and decreased monotonically during the following 35 minutes of observation time.

At the time of this flare, the spacecraft roll angle β shown in Figure 2b was equal to 72°. The altitude of the Ca xix emission region, derived from equation (2) and taking into account the spacecraft motion, is shown by the data points in Figure 3a. The error bars are derived from the uncertainty in the determination of the separation between the centers of adjacent pairs of spectra as discussed above.

The electron temperature, determined from the ratio of the lithium-like satellite k to the Ca xix resonance line (Feldman, Doschek, and Krepelin 1980), is shown by the solid curve in Figure 3b. The electron temperature peaks at 1.6 x 10^7 K and slowly decreases to a value of 9 x 10^6 K. The emission measure N_e^2 V, assuming collisional excitation of the Ca xix resonance line from the ground state, is shown by the dashed curve in Figure 3b. The emission measure curve generally follows the count rate curve except that the emission measure peaks at a slightly later time.

IV. 1980 NOVEMBER 13 FLARE

The Ca xix count rate for the 1980 November 13 flare (designated M8.7) is shown by the solid curve in Figure 4a.

This flare originated in an active region at latitude N8 and just behind the west limb. An analysis of Hα flares from this active region indicates that the active region rotated behind the west limb a few hours before the Ca xix flare (Solar-Geophysical Data 1980). The spacecraft roll angle at the time of the flare was β = 62°. The change in position of the Ca xix emission region is shown by the data points in Figure 4a. Since it is possible that the beginning of the flare is occulted by the solar limb, the change in position is measured relative to the altitude near the end of the observation period. We note in Figure 4a that the ascent speed decreases near the end of the observation period and has an interesting damped oscillatory behavior. The electron temperature and emission measure for the 1980 November 13 flare are shown in Figure 4b.

V. CONCLUSIONS

The direct measurement of the motion of the centroid of the Ca xix emission region indicates that it ascends with speeds of 20–40 km s^{-1} for 20–30 minutes following the time of peak Ca xix emission. The emission region rises to an altitude of 30,000–40,000 km above the initial position at the beginning of the Ca xix flare.

We note that the measured speed of ascent of the Ca xix emission region is less than the ion sound speed. We also note
that the Ca xix emission region of the 1981 August 3 flare is stationary during the hot initial phase of the flare. It is possible that the measured quantities (such as altitude and speed) are characteristic of both the plasma conditions and of the magnetic field structure. The irregularities in the altitude measurements for the 1981 August 3 flare at 20h38m and at 20h45m are probably due to transient events in the heating or confinement of the plasma. The oscillatory behavior of the altitude of the 1980 November 13 flare after 10h05m is probably related to the dynamic stability of the magnetic field structure.

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