PROBLEMS IN RELATING THE OPTICAL AND X-RAY EMISSIONS FROM A SOLAR FLARE

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Abstract. We evaluate the possibility that the short-lived Balmer line emission at H9 λ3835 Å of the 1972, August 2 (1839 UT) solar flare is due to heating of the chromosphere by bombarding electrons. We point out some of the problems of comparing the time behavior and spatial distribution of simultaneous hard and soft X-ray emissions. It is concluded that the present data do not justify the attribution of the short-lived optical emission to the presumed hard X-ray producing electrons.

1. Introduction

One of the most challenging problems of observational solar astronomy is the determination of the size and location of the flare hard X-ray emission (hν > 10 keV) in the Sun’s atmosphere. Indirect methods such as occultation of X-ray bursts by the solar limb have been applied with limited success by McKenzie (1975) and Roy and Datlowe (1975). These analyses are consistent with diffuse hard X-ray emission over extended regions or with a small emitting core at h ≈ 10⁴ km. However some ambiguity remains in interpreting “behind-the-limb” hard X-ray emission as shown by Brown and McClymont (1975).

Brown (1975), Brown et al. (1975) and Hoyng (1975) have shown that it is difficult to infer from the present X-ray data which way the bremsstrahlung X-rays are generated by electrons. On the other hand, many authors (Kane and Donnelly, 1971; Zirin and Tanaka, 1973; Vorpahl, 1974 and Rust and Hegwer, 1975) have inferred from the apparent coincidence in time behavior with hard X-rays of ultra-violet radiation, H9 λ3835 Å brightenings, Hα kernel emission and white light emission that the electrons which would produce the rapidly varying thick target X-ray bremsstrahlung also give rise to chromospheric emission through direct heating of the optically emitting layers. Although evidence for beams of electrons might be found in the controversial measurements of solar X-ray polarization by Tindo et al. (1973), directivity and polarization do not necessarily result from thick-target effects.

In this paper, we investigate some of the problems encountered in comparing optical and X-ray emissions from a solar flare. Specifically, we evaluate the possibility of electrons bombarding the chromosphere to give rise to synchronous

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H9 $\lambda 3835$ Å emission (Figure 1) during the 1972, August 2 (1839 UT) 1B flare at N14 E26 by comparing the time behavior and spatial distribution of the emissions.

2. Observations

In the following, study is made of the hard X-ray observations obtained with the Utrecht hard X-ray spectrometer flown on RD–1A (Van Beek, 1973). This experiment provided excellent spectral coverage at energies above 30 keV with a time resolution of 1.2 sec. Maps of XUV emission (spatial resolution $\approx 20''$) obtained by Neupert et al. (1974) on OSO-7 were compared with filtergrams at H$\alpha$ 6563 Å and at $\lambda 3835$ Å taken at Big Bear Solar Observatory (see Zirin and Tanaka, 1973); the filtergrams were taken every 5 or 10 sec during the flare. Castelli et al. (1973) and Zirin and Tanaka (1973) have commented on the microwave burst which they described as extremely hard and assumed to originate low in the corona.
3. The \( \lambda 3835 \) Å Flashes versus the Hard X-Ray Time Profile and the Soft X-Ray Spatial Distribution

3.1. Time History

Zirin and Tanaka (1973) explain the \( \lambda 3835 \) Å flashes by H9 Balmer emission which coincided with the bright H\( \alpha \) kernels. Let us first examine this identification. Inspection of the \( \lambda 3835 \) Å region on flare spectra reveals that H9 is the dominant emission feature. Machado and Rust (1974) have provided the best explanation for the continuous emission in the optical range as being due to Balmer and Paschen continua; however, continuous emission near \( \lambda 3835 \) Å due to bound-free transitions to level \( n = 3 \), to which the flare is certainly transparent as long as \( n_2H \approx 10^{16} \text{ cm}^{-2} \), is unlikely to be important for values of electron and column densities and temperature normally considered. But the latter parameters result from ideal models; the real flare may differ enough to enhance the various continuous emission processes. Furthermore, serious contamination can originate from the abundant neutral Fe and Mg lines and CN bands within the 15 Å passband at \( \lambda 3835 \) Å. In their study of the white-light flare of August 7, 1972, Machado and Rust (1974) found seven metallic lines displaying slight to moderate change of their profiles and Mg I \( \lambda 3838.3 \) Å displaying emission above the continuum. In brief, the identification of H9 as the dominant contributor of the emission observed at \( \lambda 3835 \) Å over a 15 Å passband is basically correct, but contaminating emission features, mainly metallic lines and to a lesser degree the hydrogen continua, may contribute significantly.

Bearing these remarks in mind, we consider in the following paragraphs the physical conditions leading to the observed emission as if due to H9 only. We have used the traditional formalism as described by De Feiter (1966) and Švestka (1972) to calculate the necessary column density to account for the observed intensity enhancement \( \Delta I_0 \) relative to the neighbouring continuum \( I_c \), represented by a Planck function at \( T_R = 6000 \text{ K} \) corresponding to the photospheric Balmer radiation at the Balmer limit. The relative source function was evaluated using the departure coefficients for radiative detailed balance in the Lyman lines and continuum, a dilution factor \( W = 0.5 \) and assuming \( T_e = 10^4 \text{ K} \) (De Feiter, 1966).

The ratio of the mean intensity, with spectrum lines smoothed, to the true continuum near \( \lambda 3835 \) Å is about 0.42 (Allen, 1963); the intensity ratio between penumbra and photosphere in the same spectral-region is 0.72 (Korn, 1940). Since the brightenings are located in a dark penumbral area, the mean intensity is probably less than 30% of the true continuum. The light curves shown by Zirin and Tanaka (1973) and plotted on a relative intensity scale, display an intensity increase of roughly one order of magnitude with respect to the penumbral background as seen with a 15 Å passband filter; accordingly, the estimated intensity enhancement of the Balmer H9 is likely \( \Delta I_0/I_c \approx 2 \). Figure 2 displays the range of electron densities \( n_e \) and column densities, \( n_2H \), required for various intensity enhancements of H9 \( \lambda 3835 \) Å. Because no optical spectral data are
available, we rely on calculated values of $n_e = 10^{13} - 10^{13.5}$ cm$^{-3}$ obtained by Machado and Rust (1974) and by De Feiter (1966) for numerous disk flares. This leads to a value $n_2 H \approx 10^{16}$ cm$^{-2}$. With the departure coefficients $b_1 = 7.46$, $b_2 = 7.65$ and $b_0 = 1.00$, we have $n_1 H \approx 3.4 \times 10^{20}$ cm$^{-2}$ and $n_9 H \approx 6.16 \times 10^{14}$ cm$^{-2}$ corresponding to a height of $10^3$ km above the photosphere.

The characteristic time within which the Balmer line emission should respond to electrons penetrating the chromosphere is determined by the recombination time which controls the adjustment of the ionization to the varying electron temperature. Figure 3 shows the recombination times for hydrogen defined as

$$t_R = \frac{1.6 \times 10^{10}}{n_e} T_e^{1/2} \text{ sec}$$

(1)

over the range where Balmer line emission occurs in the flaring model atmosphere calculated by Brown (1973) and Canfield (1974) who studied the Harvard-Smithsonian Reference Atmosphere structure in response to impinging electrons;
Fig. 3. Recombination times of hydrogen for the flaring model atmospheres calculated by Brown (1973) and Canfield (1974). The various curves apply to different energy inputs.

the accelerated electrons have a power-law spectrum with index $\delta = 5$; fluxes $F_{\text{20 keV}} = 10^{10}, 10^{11}$ and $10^{12}$ erg cm$^{-2}$ sec$^{-1}$ are considered. The computed thick target energy release in the chromosphere during the August 2, 1972 (1839 UT) event would amount to $2.2 \times 10^{30}$ erg over roughly 60 sec (Hoyng, 1975). If the target coincides with the $\lambda 3835$ Å brightening area ($6 \times 10^{16}$ cm$^2$), we have a flux of $6 \times 10^{11}$ ergs cm$^{-2}$ sec$^{-1}$. Therefore, a recombination time of the order of one second is implied by Figure 3, at the level of H9 formation. Moreover, since collisional recombination to higher levels followed by radiative cascade can contribute strongly to increase the effective recombination coefficient (Bates et al. 1962a, b; Mewe, 1970), recombination times of Figure 3 are at best upper limits and the flashes must appear almost simultaneous to the heating.

From Korchak (1973) it can be estimated that electrons of energy $E \geq 5 \times 10^4$ eV would penetrate a column density $n_1 H \approx 1.5 \times 10^{11} E^2 = 3.4 \times 10^{20}$ cm$^{-2}$ corresponding to the level of the $\lambda 3835$ Å flashes. Therefore, if the $\lambda 3835$ Å flashes originate almost instantaneously from the heating of the chromosphere by electrons with $E \geq 50$ keV, and since the same electrons would produce thick-target bremsstrahlung, there should be identical time behaviour between the $\lambda 3835$ Å flashes and the 53–75 keV X-ray flux.

The light curves of the three main flashing regions (described as A, B and C by Zirin and Tanaka) have been intergrated in order to compare with the X-ray flux measurements (Figure 4). Brightenings at $\lambda 3835$ Å appear at three places ($B$, $D$ and $E$) as early as 1839:04 UT. However the contributions of $D$ and $E$ (not
Fig. 4. Integrated light curve on a relative scale (thin curve) at $\lambda 3835$ Å of brightenings $A$, $B$ and $C$ as identified by Zirin and Tanaka (1973). Brightening $F$ is not included; $D$ and $E$ (also not included) were much smaller than $A$, $B$, $C$ and $F$. The hard X-ray data at 53–75 keV (thick curve) with a time resolution of 1.2 s was obtained by the Utrecht hard X-ray spectrometer on TD-1.

included in Figure 4) are not sufficient to increase significantly the H9 flux to produce an early major peak matching the one at 53–75 keV. One would expect a corresponding optical flash in the thick-target model. Better time resolution of the filtergrams might eventually reveal a flash, but present observations make it obvious that although short-lived brightenings occur during the hard X-ray phase, the detailed time behaviours of both emissions are somewhat unrelated. Furthermore, the flash identified as $F$ by Zirin and Tanaka (1973) and located just north of the sunspot group (Figure 5) is the brightest of all the $\lambda 3835$ Å brightenings; it is not included in the integrated light curve of Figure 4. The area $F$ ($\approx 2500$ km in diameter) brightens slowly throughout the flash phase and reaches its brightest after 1840 UT. Apparently, it has nothing to do with the flare impulsive phase and it is definitely unrelated to the rapid hard X-ray fluctuations. In view of the discrepancies described above and of the uncertainties inherent to the optical data, it is hard to justify the attribution of the short-lived $\lambda 3835$ Å brightening to the presumed hard X-ray electrons.
3.2. **Spatial distribution of flare emission**

Syrovatskii and Shmeleva (1971), Hudson (1972) and Brown (1973) have demonstrated that energetic electrons impinging on the chromosphere would give rise to very strong heating of the layers involved. The peak of the soft X-rays does not have to coincide with either the hard X-ray region or the optical emission; but chromospheric heating required by the thick target model should lead to some of the soft X-ray emission to coincide with those above at the time of the impulsive phase. Accordingly, if the area of the $\lambda 3835$ Å flashes corresponds to the target regions, very hot emitting plasma should overlay them. However the XUV observations reported by Neupert et al. (1974) shows that the strongly heated region of continuum soft X-ray emission (1.90–2.07 Å contours in Figure 5) as it appears at 1839:39 UT during the phase of hard X-ray emission, is displaced* along the north–south axis of the Hα emission by about $3 \times 10^4$ km to the north of the center of gravity of the $\lambda 3835$ Å emission. In order to account for this northward shift by projection effects, the hot cloud must be located at $2 \times 10^5$ km above the Balmer emission. This large value is due to the heliocentric latitude of the Earth, $B_0 = +5.9^\circ$; therefore the center of gravity of the flare is located at

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* The Goddard experiment operated a Hα system with the XUV spectroheliograph. Comparison of these allows to properly register XUV maps with high-resolution ground-based optical observations; see Neupert et al. (1974).
N08 E26 with respect to the subsolar point. However it is difficult to reconcile this with the apparent lack of eastward shift of the soft X-rays, unless we assume that this emission originates above a location $10^5$ km west of the Balmer flare indicated by X in Figure 5. Because of the unlikeliness of such a remote source, we conclude that projection effects are negligible and that the source of soft X-rays is in the low corona, and displaced from the strongest Balmer emission.

4. Concluding Remarks

With the present uncertainties, it is unjustified to conclude that the $\lambda 3835$ Å short-lived brightenings arise from the heating effects of the would-be producing hard X-ray electrons. One remains free to investigate other mechanisms than fast particles for inducing flashes of chromospheric emission (e.g. Uchida, 1975), since protons are also deficient in energy by at least one order of magnitude (Zirin and Tanaka, 1973).

We have assumed in Section 3.1 that the time lag existing between the heating of the optical flare region and the appearance of the optical emission is the recombination time which controls the adjustment of the ionization. Brown (1975, personal communication) has pointed out that H$\alpha$, Ly$\alpha$ and the Ly continuum are optically thick and so are slow to average; because these transitions govern the departure coefficients of higher levels, there may be a time lag much larger than the one specified by Equation (1). The concept of simultaneity of hard X-ray and optical emission might turn out to be irrelevant once the time-dependent radiative transfer problem in a flare has been worked out. Only simultaneous high time (1 s) and spatial ($\approx 10''$) resolution observations of hard X-rays and optical emissions at various wavelengths could eliminate the numerous observational ambiguities faced by theoretical interpretation.

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