He D₃ AS A DIAGNOSTIC FOR THE HARD AND SOFT X-RAYS FROM SOLAR FLARES

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ABSTRACT

We have studied the time comparison of He D₃ and X-ray emission in a number of medium-sized flares. In most cases there is a good agreement between the time histories of the He D₃ emission and the high-temperature (~2 keV) thermal source.

The most intense He D₃ emission comes from two small regions on either side of the neutral line, which we identify with the footpoints of magnetic structures in which a hot (2.3 x 10⁷ K) thermal plasma is formed. The impulsive X-ray event is marked by the transient brightening of a number of (usually weaker) He D₃ sources. The two types of sources are well displaced from each other, which is an indication that they are produced in two different plasma volumes.

In some cases a long-lived third He D₃ source is seen.

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

I. INTRODUCTION

Over the years reliable observations of solar flares have been obtained through almost the entire electromagnetic spectrum, reflecting the different emissions excited by the flare in different parts of the solar atmosphere. Some of these emissions are produced directly by the flare particles, and others represent secondary emission by the chromosphere or corona. In some of these (such as very hard X-rays) only flux versus time signatures have been recorded. In others (soft and medium hard X-rays), imaging is achieved, but with limited spatial resolution. In microwave images the resolution is high but the spatial frequencies and dynamic range are limited.

One should also recognize the difficulty of coaligning the data obtained from the different energy bands without a priori knowledge of the relative locations of emitting features. This is particularly difficult with spacecraft data, where there is not an absolute coordinate frame available for each instrument. Even when absolute positions can be obtained, as in microwave and in optical data, it is hard to compare positions to better than 4" (Marsh, Zirin, and Hurford 1979). In summary, it is difficult to determine the temperature structure of the flare because of the difficulty in coaligning the emission that represents different temperature regions of the flare.

Finally, the number of events which have been imaged in X-rays or radio waves is still small, while a large number of events have been recorded by nonimaging detectors. It would, therefore, be of considerable benefit if the site of high-temperature flare emission could be inferred from observational data that also showed the location of the low-temperature flare as well as magnetic field geometry. In this paper we address this issue with data obtained at optical wavelengths.

Optical flare observations have the advantage of excellent spatial frequency coverage, good spatial resolution, fair time resolution, and a large body of data. Even more important, the crucial magnetic fields are recognizable only in optical wavelengths, so data can be immediately related to known features such as sunspots and neutral lines. With improved techniques, film records are now available not only in Hα but also in the Hβ, Mg I b, Na I D, and He I D₃, as well as various continua such as λ3862 and the G band at 4305 Å. Observations in all of these wavelengths have been made at Big Bear and are available for study.

Zirin (1978) studied the connection between Hα and X-ray time profiles and found an impulsive rise in the Hα emission simultaneous with the impulsive hard X-ray (HXR) burst and a decline parallel to the soft X-ray (SXR) burst. He also found a suggestion that the Hα emission connected with SXR is low lying and not visible in limb flares. Since that time much better X-ray data have become available from International Sun-Earth Explorer (ISEE 3) and Solar Maximum Mission (SMM), and more comprehensive SXR spectra from NRL and
Aerospace Corp. experiments on the Air Force spacecraft P78-1.

Although Hα tends to saturate so easily that it is difficult to separate flare kernels from less important emission sites, we (Zirin et al. 1981) were successful in identifying in the flare of 1981 March 31 Hα loops that corresponded to the sites of SXR emission. These loops were formed shortly after the start of the SXR emission and were closely associated with the SXR event. The structures remained bright until just after the SXR maximum. The loops were about 10″ long and formed an arcade 10″ across. This result fitted the emission measure deduced for the event from X-ray lines as well as the Skylab flare observations (Widing 1975) which showed the high ionization lines to come from the loop tops. Similar results were obtained for several other events for which less complete data were available.

We felt that the best hope of recognizing in the visible part of the spectrum the sites of the main energy source of the flare was to use a line less sensitive than Hα. The He D₃ line (λ = 5876 Å) was chosen because it is (1) optically thin, (2) sensitive to excitation, and (3) seen against a structureless background. A large body of data in this line had been accumulated at Big Bear. Since the He D₃ line is normally not seen against the disk, it may represent the main site of the flare and therefore will be less confusing than the images seen in more complex lines such as Hα. However we feel that data in Mg b, Na D, and Hβ will not give greatly different results in larger events where chromospheric confusion is less important.

The He D₃ line is known to appear in both absorption and emission in flares. It results from transitions between the 1s2p⁴P and 1s3d⁴D terms. In most instances it is expected to be optically thin. Its appearance in emission can be attributed to the presence of a high-density plasma in which the excitation rate by collisions is so high that it becomes more important than normal radiative excitation and decay. In this case excitation in the line exceeds that produced by normal photospheric fluorescence, and an emission line results (Zirin 1978). At lower densities collision rates are low and the high UV radiation field in flares excites the lower level of the line, producing absorption. The fact that emission appears only at lower projected heights shows that the ambient density is critical to the excitation rate, implying that the emission is produced by thermal heating of the lower levels. Thus the appearance of He D₃ in emission signals a high-temperature (> 15,000 K), high-density (> 10¹⁴ electrons cm⁻³) plasma.

In 1973 a Halle Hα filter was converted by Spectra-Optics (Mr. Doug Martin) to use in He D₃ (with a bandpass of 0.4 Å), and regular observations of active regions in the He D₃ line were begun at Big Bear. Observations of flares in He D₃ have been reported by LaBonte (1978a, b), Zirin (1980), and Zirin and Neidig (1981).

In general the observations show what would be expected: in lower energy eruptions such as surges, erupting prominences, and flare ejecta, absorption in the He D₃ line is seen. In flares, quite bright kernels, up to twice the photospheric intensity, are seen.

II. OBSERVATIONAL DATA

Observations in He D₃ are made regularly at Big Bear either with the Halle filter mentioned above or with the Zeiss Universal birefringent filter (0.2 Å bandpass). They are made either with the 25 cm or the 65 cm telescope, recorded on Kodak 2415 emulsion at a rate of 4–6 frames per minute. At the same time observations are made in three other wavelengths of those noted above, invariably including Hα.

We selected a number of simple flares in which He D₃ emission was observed. Some more complex He D₃ flares were added later. The time dependence of most He D₃ emission kernels was measured with an overhead 35 mm projector and a photodiode. Only frames with

### TABLE I

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*Difficult to determine thermal maximum.

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20–37 keV and 12–20 keV ISEE 3 data.

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good seeing were used, because bad seeing diffuses the kernels and artificially lowers their brightness.

The X-ray data were obtained from *ISEE 3*, supplemented by *SMM* data. In Table 1 we have listed the flares studied, together with information on the maxima in He D₃ and in thermal X-rays. In order to determine the peak of the thermal X-rays, the 26–43 keV channel or a combination of 10–14 keV and 26–43 keV channels was used unless noted otherwise.

III. RESULTS

The original group of flares used in this analysis was chosen according to the detection of bright emission in He D₃ movies. The X-ray signatures of the flares showed that most had both HXR and SXR emission, but two were found to have no HXR emission in the data from *ISEE*. Those flares (19:01 UT, 1979 November 6 and 17:27 UT, 1980 November 6) showed no X-ray emission at energies greater than 43 keV. The time profiles of the 26–43 keV and lower channels were not impulsive. Although 26–43 keV is normally considered “hard X-rays,” intensities from the various channels of *ISEE* observed here can be fitted by a 2 keV plasma with an emission measure of ~10⁴⁹ cm⁻³.

In Figures 1 a and 1 b we plot the intensities of He D₃ and the 26–47 keV X-rays against time. The plots show the close time correspondence of the two. Figures 2 and 3 present pictures of the two flares in He D₃ during their lifetime. In the sixth panel an Hα image recorded at flare maximum is also included. The location and size of the points of He D₃ emission do not change significantly during the course of the event. The sizes of the He D₃ emission areas are on the order of 3′′–4′′ while their separation is about 10′. Measurements of X-ray images from the thermal component of flares observed by *Skylab* (Widing 1975), P78-1 (Landecker and MacKenzie 1980), and *SMM* produce similar sizes. The kernels in the 1979 November 6 flare are seen near the limb but have projected vertical dimensions less than 1′. Since they are seen projected against sunspot penumbrae in the correct position, they are probably not more than a few seconds above the photosphere in height.

In all cases we found the brightest He D₃ emission in two stationary footpoints of opposite magnetic polarity as indicated from magnetograms or their Hα location on opposite sides of the neutral line. These are indicated in all the figures as A and B. Often the footpoints are at the inner edge of the sunspot penumbra.

From these facts we conclude that the flare regions of bright He D₃ are footpoints of magnetic structures (perhaps loops) which contain the thermal flare.

The flares of 23:47 UT, 1979 November 5, and 15:43 UT, 1979 October 22, are examples of events in which impulsive HXR components are also present. Figure 1c shows the intensity versus time in the 26–43 keV and 43–78 keV channels in the October 22 flare. Figure 1d shows the intensity: time profile in the 12–20 and 70–168 keV channels in the November 5 flare. The X-ray signa-
Fig. 2.—He D$_3$ images of the 1980 Nov 6 flare. The SXR maximum was at 17:26:34 UT. Points A and B indicate the footpoints of the thermal X-ray event in this as well as the other illustrations. An image of the Hα flare appears in the last panel.
Fig. 3.—He D$_3$ images of the 1979 Nov 6 flare, which occurred near the limb. SXR maximum was at 19:02:49 UT.
Fig. 4.—He D images of the 1979 Oct 22 flare. SXR maximum was at 15:43:56 UT. HXR maximum was at 15:42:53. Points C in this figure and in Figs. 5 and 6 indicate the signature of the impulsive event. Point D (also in Fig. 5) indicates the "third kernel," a round, diffuse, long-lived, isolated feature linked with the SXR, but lasting even longer.
Fig. 5.—He D\textsubscript{3} images of the 1979 Nov 5 flare, X-ray maximum 23:47:30. A videomagnetogram appears in the last panel, with the opposing polarity of the footpoints A and B marked.
Fig. 6.—He D$_3$ (left) and λ3862 continuum in the 1980 July 1 flare. The SXR footpoints A and B are brightest in He D$_3$, while the HXR kernels C are brightest in the continuum. Point D, however, is bright in both.
tatures in the higher energy channels are purely HXR emission, while the low-energy channels are a superposition of the thermal and the impulsive events. A differencing of the two gives the true shape of the thermal components. Figures 4 and 5 show the He D₃ images during the lifetime of the events. Notice that the time history of the bright points marked by A and B resembles rather nicely the time history of the thermal component. The points marked C appear only during the impulsive event. In the 1979 November 5 flare the impulsive event peaked at 23:47:00 UT, and in the 1979 October 22 flare it peaked at 15:42:40 UT. We believe that the images A and B are the footpoints of the thermal loop while C is a site of the impulsive HXR emission. Kane et al. (1982) observed the 1979 November 5 flare from two spacecraft and found that at least 50% of the emission came from below 2500 km. This is confirmed by our results. Note that the images of the two different X-ray emissions are separate and must originate in different plasma volumes. This same conclusion was reached by Feldman, Cheng, and Doschek (1982) from P78-1 X-ray data.

Upon close inspection many of the He D₃ “footpoints” appear to be comma shaped, perhaps themselves loops. Since they are located in one magnetic polarity, it would be difficult for us to explain the presence of loops in a unipolar region.

Since the He D₃ images produced by the thermal component are probably produced inside loops at some height above the photosphere, while the He D₃ images produced by the impulsive event are perhaps a result of fast particles bombarding the photosphere, it is expected that the footpoint images will be dominant in images produced by emission lines (like He D₃) while the impulsive images will be the dominant component in white-light pictures. This is true in the more complex flare of 1980 July 1 shown in Figure 6 (Zirin and Neidig 1981; Zirin and Tanaka 1981), and indeed one can see that the kernels A and B, which have a time history similar to the thermal event, are intense in He D₃ and faint in white light while kernel C shows the reverse behavior. The 1980 July 1 flare shows another feature (here marked point D, also referred to as point C by Zirin and Neidig) which becomes the brightest feature late in the flare, at the peak of the hot thermal X-rays. We have found similar features in most of the He D₃ flares. They are distant, round, diffuse, and long lived, usually less bright than the two thermal footpoints. They also are marked by bright Hα. They are marked D in those figures which show this. While they are apparently connected by field lines to the main flare, their location has no particular distinction.

The rest of the flares mentioned in Table 1 have been carefully investigated and show results similar to the ones discussed above.

### IV. Conclusions

In many flares we could separate clearly the impulsive HXR burst and the hot thermal SXR burst. These always gave distinctive patterns in images taken in He D₃ emission.

The impulsive burst normally comes during the rise phase and is marked by a number of small, irregularly shaped transient brightenings, most of which (but not all) are along the neutral line. These normally fade with the end of the impulsive phase. They are similar to the continuum flashes reported by Zirin and Tanaka (1980) in the 1972 August 2 flare.

The He D₃ emission corresponding to the thermal burst consists of two intense regularly shaped kernels on either side of the neutral line. They are long lived, matching the time profile of the hot thermal SXR burst. In some flares we can see postflare loops connecting them. They are much brighter than the He D₃ flashes associated with the HXR burst, and peak after it. In many cases there is a third, distant component which is usually round and diffuse.

The He D₃ kernels are usually about 1" across for the impulsive burst and 3"–4" across for the footpoints of the hot thermal event. They often are comma or loop shaped. The footpoint separation is about 10" for a class 2 flare. The hot thermal plasma must be localized in the loops connecting these small areas.

The presence of a hot thermal component (in contrast to the cooler thermal plasma of the decay phase) unrelated to the impulsive spike was recognized by Feldman, Doschek, and Krepelin (1980) in soft X-ray spectra and by Lin et al. (1981) in high-resolution energy spectra of the 1979 June 27 flare. It is easy to show that the high-energy tail of the emission from this component can make a considerable input to X-rays measured at energies below 40 keV. The energy spectrum of this soft component as deduced from ISEE shows that it indeed corresponds to a 2 keV thermal plasma.

We have not carried out calculations for the excitation of He D₃ by the thermal plasma. That plasma is known to involve considerably more energy than the impulsive electrons. This energy is transmitted downward quite rapidly, as we have seen. The energy emitted in He D₃ for a class 2 flare is about 10²⁵ ergs s⁻¹.

Although we can now separate impulsive from thermal flares rather readily using the considerations discussed here, their connection is still a mystery. The impulsive burst always occurs early in the flare, but there is often a still earlier increase in the SXR emission as the flare starts up. The footpoints of the impulsive flare are all over the active region, while the main thermal footpoints in He D₃ are concentrated in the main part of the flare, i.e., the brightest Hα kernels, neutral line microwave source, etc. It is tempting to speculate that the impulsive burst is associated with the
initial restructuring of magnetic field, and the hot thermal phase with the "main phase" energy release.

We wish to thank Sharad Kane for supplying us with much ISEE 3 data as well as for the various helpful discussions we have had with him. We also thank Alan Kiplinger for his willing compliance with our many requests for SMM (HXRBS) data. The operation of the Big Bear Solar Observatory is supported by the Solar Terrestrial Program of the NSF under ATM 8112698 and NASA under NGL 05 002 034.

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