ANALYSIS OF 2-D FLARE SPECTRA: VELOCITY FIELDS DERIVED FROM Hα LINE ASYMMETRIES

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Abstract. We derive a time series of two-dimensional velocity fields for a flare region on 1992 December 16, based on the asymmetries of the Hα line. The Hα spectra were obtained by an imaging spectrograph at the Solar Tower Telescope of Nanjing University. Four sites with evident chromospheric downflows are found to appear and decay consecutively in the studied region. The value of maximum velocities is 30–40 km s⁻¹ and the lifetime of downflows is 2–3 min at these sites. It is also shown that the asymmetries only exist at the line wing, while the line center has nearly no shifts for this flare. Finally, we make a discussion on the characteristics of the velocity distribution and its correlations with the intensity distribution, as well as with the hard X-ray emission.

1. Introduction

The Hα line has been widely used as a diagnostic tool for the physical conditions of the chromosphere during solar flares. Canfield, Gunkler, and Ricchiazzi (1984) computed Hα line profiles from static atmospheres and found that the shape of profiles depends greatly on the flare conditions, including the nonthermal electron precipitation, heat conduction, and enhanced coronal pressure. Canfield and Gayley (1987) further computed Hα line profiles from a dynamic atmosphere (Fisher, Canfield, and McClymont, 1985) and showed that different parts of the profile respond at different time scales to the flare heating. These studies imply that the Hα line contains important information relating to the flare energy release and transport processes.

One of the most evident signatures in Hα lines of solar flares is the red asymmetry of the profiles. The great majority of Hα spectra observed so far in flare kernels exhibit such a property (e.g., Ichimoto and Kurokawa, 1984; Zarro et al., 1988; Wülser and Marti, 1989; Zarro and Canfield, 1989; Canfield et al., 1990a, b; de la Beaujardière, Kiplinger, and Canfield, 1992; Falchi, Falconi, and Smaldone, 1992; Wülser, Zarro, and Canfield, 1992; Wülser et al., 1994), though, in some cases, the blue asymmetry of Hα line profiles may also appear and persist for a rather long time (see Heinzel et al., 1994 and references therein). The red asymmetry has been interpreted as a consequence of chromospheric downflows with velocities of tens of km s⁻¹. The origin of the downflows may be related to the chromospheric condensations, which are believed to result from the impulsive heating at the top of the chromosphere and accompany the formation of chromospheric evaporations (Fisher, Canfield, and McClymont, 1985). De la Beaujardière, Kiplinger, and Canfield (1992) have calculated the temporal evolution of the downward velocities and
found that the slowing-down time is about 4 times longer than the value predicted in a theoretical model (Fisher, 1989).

In previous works, much attention has been paid to the spectral characteristics in only one or a few fixed points in the flare region (particularly in flare kernels). This has the advantage of reaching high temporal resolution, but is difficult to reveal the morphology of flare phenomena. Recently, the technique of the imaging spectrograph has been used to obtain two-dimensional (2-D) spectra of flare regions (e.g., Wülser and Marti, 1989; Canfield et al., 1990a; de la Beaujardière, Kiplinger, and Canfield, 1992; Graeter and Kucera, 1992). These spectra show that distinctly different spectral features may exist at different locations.

The main purpose of this paper is to study the 2-D distribution of chromospheric velocities indicated by the Hα line asymmetries. We use the 2-D spectral data of a flare on 1992 December 16, observed by the Solar Tower Telescope of Nanjing University. The paper is organized as follows. In Section 2 we describe the observing instrument and the observed flare event. Section 3 presents the data analysis method and the results. Finally, a discussion of the results and some main conclusions are given in Section 4.

2. Instrumentation and Observations

In recent years, a CCD imaging spectrograph was mounted at the Solar Tower Telescope of Nanjing University. This system is used to record 2-D spectra replacing the previous fixed-slit spectral observations. Two CCD cameras are operated with one for the Hα line and the other for the Ca II K line. Generally, we record 112 pixels along the spectrograph slit with a pixel spacing 1.46″. The region to be observed is scanned by the slit for 30–60 steps each time, with one step corresponding to 2″. For each space pixel, the spectrum has 224 spectral channels, covering about 9.4 Å wavelength range for Hα and about 12.1 Å for Ca II K. With the present data acquisition and data storage capabilities (an image processor SR151 and a personal computer DX486), the scan repetition rate is 10–15 s, depending on the step number needed for each scan. In the observations prior to 1993, the repetition rate is about 5 s slower than this.

The CCD imaging spectrograph at Mees Solar Observatory (Penn et al., 1991) has a spatial resolution 2.4″, a time resolution 12 s and a spectral resolution 0.38 Å pix⁻¹, when it is used for flare observations. The instrument used by Wülser and Marti (1989) has a spatial resolution 3″ and a much higher time resolution 2.3 s, but it has only 25 spectral channels with spacing varying from 0.25 Å at line center to more than 0.5 Å in far wings. Compared to these parameters, our instrument has particularly increased the spectral resolution. This enables us to perform detailed spectral analyses for flares.

The flare to be studied in this paper occurred on 1992 December 16 in the active region 7360 (S20 W55). According to the Solar Geophysical Data, it was a small
event with the Hα importance SF and soft X-ray class C4.6. Our observations were made between 03:14 UT and 03:32 UT, covering the maximum phase of the flare. Only the Hα camera was operated in this time. A total of 24 frames of 2-D Hα spectra were recorded.

3. Data Analysis and Results

3.1. Method for Deriving Velocities from Line Asymmetries

Generally, it is difficult to infer the exact mass motion velocities from the asymmetries of an optically thick line, especially in the case of large velocity gradient. A relatively accurate method is to make detailed computations of line profiles from the atmosphere with the existence of various velocity fields. The most probable velocity value can be found by comparing the calculated profiles with the observed one. The application of such a method can be seen in a recent paper by Gan, Rieger, and Fang (1993), in which the observed line asymmetries are well explained by down-moving chromospheric condensations. However, this method is still model-dependent and greatly time-consuming, thus impractical to the analysis of 2-D spectra owing to the enormous number of spatial pixels.

Therefore we adopt the simpler but widely used method, that is, to extract the velocity value from the Doppler shift of the line profile bisector. We should admit that the reliability of the bisector method is changed from flare to flare, and even from pixel to pixel. Some detailed computations have shown the complicated correlation between the velocity field and the line asymmetry. Recently, Heinzel et al. (1994) found that a downward velocity field in the transition region and upper chromosphere would produce a blue asymmetry of the Hα line. Gan, Rieger, and Fang (1993) also showed that the downward-moving chromospheric condensation can not only explain the Hα red asymmetry, but also the blue asymmetry, if one changes the parameters of the condensation. On the other hand, it has long been known that an expanding atmosphere would sometimes cause the red asymmetry of spectral lines (e.g., Hummer and Rybicki, 1968). This is to say, the bisector method fails to yield the correct results in some special cases. However, for the flare studied in this paper, only red asymmetries of the Hα line are found to exist, and we assume that the asymmetries are produced by chromospheric downflows. In this meaning, the velocity value derived from the bisector method can reflect a ‘mean’ effect of downflows in the line-forming region.

In the computations, it is necessary to distinguish between the flaring region and the undisturbed one. This dichotomy is made by comparing the line-center intensity with a critical value, above which the line profile is considered as an emission one and we use the difference profile (the flare profile with subtracted preflare one) to determine the velocity, otherwise the line profile is treated as an absorption one and we simply use the original profile to obtain the velocity. The reason for doing
so is that the difference spectra are formed mainly in the perturbed part of the atmosphere and can better reflect the mass motions which may exist there. Figure 1 gives examples of a typical flaring region profile and a typical undisturbed region profile, and also shows how the velocity values are derived in these two cases.

The preflare spectra should best be obtained well before the flare eruption. Unfortunately, we did not perform such observations for the 1992 December 16 flare. This leads to an uncertainty in the determination of Hα difference profiles. Considering that the flaring region lies well apart from the sunspots in this active region, we use a quiet-region reference profile to replace the preflare profiles for the whole observed region. This will inevitably result in some quantitative errors for the derived velocity values, especially in the area where the preflare conditions resemble a plage. However, it only has minor influence on the general characteristics of 2-D velocity distributions.

3.2. 2-D VELOCITY DISTRIBUTIONS OF THE FLARE REGION

According to the method described above, we can compute the Doppler shift of the bisector of the difference or original Hα profile for each space pixel. The critical value of the line center intensity is arbitrarily set to be 1.3 times the value
of the quiet-Sun reference profile. Considering that the profiles at different pixels vary greatly, we compute the velocities corresponding to the Doppler shifts at the same emission or absorption level relative to the line center, in order that they can reflect the mass motions at roughly the same height in the atmosphere. For the 1992 December 16 flare, it has been found that the line asymmetries at most pixels increase significantly from the line center to the line wing. Below, we will firstly demonstrate the 2-D distributions of the velocity derived at a wing level, with emphasis on their temporal evolution and their relationship with the distributions of the line intensity. Secondly, we give an example to show how the velocity fields change with the emission or absorption levels at which they are derived.

Figure 2 presents the 2-D distributions of the intensity at the H\(_\alpha\) line center and at the red wing (\(\Delta \lambda = 1 \text{ Å}\)), and the velocity derived at the level of 20% of line center emission or absorption (see Figure 1) for 9 times selected from the whole set of 24 ones. The intensity contours in Figure 2 show the general morphology of the flare. At the line center, the flare has two main kernels, while at the red wing, there seem to exist several bright patches, which may correspond to the 'footpoints' of this flare. The bright patches at the red wing do not coincide exactly with the kernels at the line center. This may imply a fact that the effective heating heights are different in different regions.
Fig. 2. Contours of the intensity at the H\(_\alpha\) line center \(\Delta \lambda = 0\) Å (left column), the intensity at the H\(_\alpha\) red wing \(\Delta \lambda = 1\) Å (middle column), and the velocity derived from the Doppler shift of the line-profile bisector at the level of 20\% of line-center emission or absorption (right column). The three panels in each row were observed at a same time. The contour levels are 1.5, 1.8, 2.1, 2.4, 2.6, 2.8 \(\times I_{\text{center}}\) (solid lines) and 0.90, 0.85, 0.80 \(\times I_{\text{center}}\) (dashed lines) for the line-center intensity, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35 \(\times I_{\text{wing}}\) (solid lines) and 0.90, 0.85, 0.80 \(\times I_{\text{wing}}\) (dashed lines) for the line-wing intensity, and 8, 16, 24, 32, 40 km s\(^{-1}\) (solid lines) and \(-8, -16, -24, -32\) km s\(^{-1}\) (dashed lines) for the velocity. Here, \(I_{\text{center}}\) and \(I_{\text{wing}}\) represent the line-center intensity and the line-wing intensity of the quiet-Sun reference profile, respectively. The field of view for all panels is 80'' \times 50''.
Fig. 2 (continued).
The velocity fields display much more interesting phenomena. Throughout the development of the flare, we can find four regions (marked with 'A', 'B', 'C', and 'D') with evident downward mass motions. There are some differences in their dimensions and velocity values. For example, the maximum velocities in regions A and C are nearly 10 km s\(^{-1}\) greater than those in regions B and D; the dimensions of regions A and D are larger than those of regions B and C. Moreover, the temporal evolution behaviours of the velocities in these regions are also distinctly different. There exists a time sequence for the appearance of regions A, C, and D: A is the first to exhibit observable velocities; C is the second; D is the last. The same is applied to the times of peak velocities (see panels of 03:15:35 UT for A, 03:16:23 UT for C and 03:17:03 UT for D, respectively). The time interval between A and C or between C and D is about 40–60 s. In spite of these differences, the lifetime of velocities in A, C and D are all about 2–3 min. Region B may be an exceptional case. It appears nearly as early as region A, but it decays much faster. Through a detailed comparison, we can further find that regions with evident downflows always correspond to the 'footpoints' (regions with enhanced red-wing emissions) of the flare (see, e.g., panels of 03:15:58 UT for A, 03:16:41 UT for C and 03:17:03 UT for D, respectively). However, there is no clear correlation between the intensity and the velocity values. For example, region D is the brightest, but its velocity value is not the largest. As restricted by the time resolution, we are unable to study the temporal relationship between the peak intensities and the peak velocities for a specific region, which may be done in fixed-slit spectral observations (e.g., Fang et al., 1992).

Figure 3 plots the velocity distributions derived at different emission or absorption levels for the time of 03:16:23 UT. It shows that the line asymmetries for this flare only occur at the line wing, while there is nearly no shift at the line center. The velocity values depend very sensitively on the levels, implying that the line bisectors have some gradients (see also Figure 1(a)). This phenomenon also appears in some previous observations.

3.3. COMPARISON WITH HARD X-RAY DATA

Figure 4 shows the time profile of hard X-ray emission at the 14–23 keV energy channel for the flare observed by the hard X-ray telescope (HXT) on board the Yohkoh spacecraft (Kosugi et al., 1991). Also shown in the figure are the downward velocity evolutions of regions A, C and D, displayed in Figure 2. The velocity values are an average over a circular area with a diameter 6\(\prime\), centered on the pixel exhibiting the maximum velocity in each region. From the figure, it can be seen that there exist multiple hard X-ray emission peaks, of which three main ones are indicated by dotted lines. These peaks have a rough temporal correspondence with the maxima of downward velocities, for example, the second peak with region A and the third peak (including several subpeaks) with regions C and D, on consideration that there may be a time delay of $H\alpha$ redshifted emission relative to the hard X-ray...
Fig. 3. Contours of the velocity derived at different emission or absorption levels (denoted by the numbers shown at the upper-right corner of each panel) for the time of 03:16:23 UT. The contour levels are the same as in Figure 2.
emission. This implies that nonthermal electron precipitation may play at least a partial role in the heating of the flare atmosphere.

4. Discussion and Conclusions

The 1992 December 16 flare is only a small event. The emission amplitude of the Hα line is not very high, and the line profiles are relatively narrow (with a full width at half maximum less than 1.4 Å), even at the brightest kernel. However, the Hα profiles are red-asymmetric at most regions with enhanced Hα emissions, similarly to some previous major events. The value of maximum downward velocities derived in this paper is 30–40 km s⁻¹, as shown in Figure 2. This value is less
than the maximum velocities found by Ichimoto and Kurokawa (1984), Zarro et al. (1988) and Wölser and Marti (1989), but is comparable with those in Canfield et al. (1990b) and Wölser et al. (1994). Such chromospheric downflows would be most probably associated with the dynamics of chromospheric condensations (see, e.g., Fisher, Canfield, and McClymont, 1985). However, there are two major problems to be solved. Firstly, why is the line center nearly not shifted while the line wing shows great asymmetries? This problem has been raised in early studies (Švestka, 1976) and has been frequently reiterated in recent literatures (see, e.g., Fang et al., 1992). From the qualitative point of view, the condensation originates primarily at the top of the chromosphere, thereby it may first affect the Hα line center which is formed there. A possible explanation is that the transit time of the condensation across the forming region of the Hα line center is very short so that our observations have not resolved it. Secondly, the life time of the downward velocities (2–3 min) is apparently longer than the theoretical lifetime of the condensation (~1 min) predicted by Fisher (1989). Similar conclusions can be obtained from the observations of Ichimoto and Kurokawa (1984) and de la Beaujardière, Kiplinger, and Canfield (1992). Fisher (1989) has interpreted this discrepancy as a consequence of the superposition of several condensations within an unresolved region. If this is true, the peak velocities in these condensations would be considerably larger than the presently derived values. The above two problems and whether there exist other causes of the Hα red asymmetry besides the chromospheric condensation deserve to be further studied in the future.

As mentioned in Section 3, the regions with evident Hα red asymmetries correspond approximately to the ‘footpoints’ of the flare. This is also to say, chromospheric downflows are most likely to exist where the flare heating can penetrate into deep layers. Additionally, it is also important to point out that regions A and B are just located near the edge of the flare ribbon shown in the Hα line center (see Figure 2). This is a clear evidence supporting the discovery of Švestka, Martin, and Kopp (1980) that red shifts are primarily confined within the leading edge of flare ribbons.

Finally, we should make a comment on the projection effect, as the 1992 December 16 flare occurred at a heliocentric angle of 57° (μ = 0.54). The Doppler velocities presented in Section 3 can only represent the line-of-sight components. The real velocities would be somewhat larger. It is, of course, difficult to infer the vector velocities at the present situation because we do not know the exact orientation of the flare loop. Therefore, simultaneous vector magnetic field or soft X-ray observations would also be required in the future to overcome this difficulty.

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References