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Derivation of the downward velocity of the flaring region of 26 June 1999

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Abstract In the present study, three methods have been used to compute the downward velocity of the flare plasma of the solar flare on June 26, 1999. The first method is used to determine the plasma velocity of the studied flare from the Hα line asymmetries by using the asymmetry method developed by Edward (2009). The second one is to obtain the downward velocity of the flare plasma from the far wings of the excess profiles by the bisector method. This method was employed by; for example, Ichimoto and Kurokawa (1984), Falchi et al. (1992), and Ding et al. (1995). The third method is the modified cloud model which is described by Liu and Ding (2001a,b), Gu and Ding (2002), Semeida et al. (2004) and Berlicki (2007).

1. Introduction

Different models and methods have been proposed by different authors to detect and measure the macroscopic downward velocity through the analyses of the line profiles of different line spectra of solar flares. But the obtained results are far from being conclusive even in the case of the photosphere and the diagnostics of downward velocity. Spectral lines in solar flares typically indicate the profile asymmetry. This phenomenon contains information on the downward velocity present in different depths of the solar atmosphere affected by abrupt heating or various non-thermal flare processes. As the spectral lines of various chemical elements originate at different heights of the solar atmosphere, they can be used for diagnostic of the spatial distribution and time evolution of downward velocity in the flaring atmosphere.

Usually the red asymmetry is interpreted as a consequence of downward motions of cool and dense plasma which is known as *chromospheric condensation* with downward velocities of the order of tens km/s. Origin of these motions is most probably due to a fast heating of upper chromospheric layers which is caused by particle beams during the impulsive phase

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of a flare. A small but long lasting blue shifts in the Hα line core in a two-ribbon flare have been observed by Schmieder et al. (1987) who interpreted them as a consequence of upward mass motions with upward velocities up to 10 km/s. They called this *a gentle evaporation*. During the impulsive phase of a flare the energy is transported by beam of non-thermal particles which proceed from the corona to the chromosphere and cause an explosive heating. However, if the energy flux transferred by these particles is low, gentle evaporation takes place due to other heating and dynamical processes. One can assume that it arises after the primary energy release and after thermalization of electron beams. These physical conditions prevail during the gradual phase of a flare (Berlicki et al., 2005). Asymmetry of a spectral line profile arises from motions of a flaring atmosphere. Therefore, detection of asymmetries can be used as a tool for studying such motions and for testing of different flare models.

Most extensive data available is for Hα line. Strong asymmetries are mainly red but also blue have been detected during the impulsive phase of a flare; Ichimoto and Kurokawa (1984), Canfield et al. (1990a,b), Heinzel et al. (1994) and others.

2. Overview

One of the most evident signatures in Hα lines of solar flares is the red asymmetry of the profiles. Such line profile asymmetries were discovered and recorded for the first time by Waldmeier (1941). The emission width in the red wing of the Hα spectral line in flares was broader than the blue wing. A statistical study of 244 Hα spectra of 92 flares by Svestka et al. (1962) revealed that, 80% of flares have at least one region with red asymmetry, 32% with blue asymmetry and only 5% of flares however show exclusive blue asymmetry. On other hand, it has long been known that an expanding atmosphere would sometimes cause a red asymmetry of spectral lines as shown by Hummer and Rybicki (1968). Severny (1968) found similar results with limb flares with the exception of more than 14% that showed exclusive blue asymmetry. Athay (1970) measured the velocities for the Hα line and got that, these velocities are very often greater than the actual velocity and very often less than the actual velocity.

In 1976 Svestka concluded that the red asymmetry is a phenomenon observed in most flares and it has been interpreted as being due to Doppler shifts from vertical mass motions in the flare region and summarized that the highest velocity is found for hydrogen (~100 km/s) (Svestka, 1976). Smaller velocities are deduced from helium and Ca II, H and K lines (a few tens of km/s), while the velocity in metals is close to 10 km/s. The time scale of the impulsive phase is of the order of seconds. In 1993, Shoji and Kurokawa successfully obtained the impulsive phase spectra in five wavelength regions simultaneously with sufficiently high temporal resolution (Shoji and Kurokawa, 1993). Studies of photometric Hα profiles of 24 flares of class 1 (larger flares) recorded with a multi-slit spectrograph have been done by Schoolman and Ganz (1981). All events studied reveal significant shifts toward longer wavelengths and most of those with unequal emission peak intensities in the self-reversal profile are also red dominant with only a few exceptions where the blue peaks are slightly brighter.

Frances Tang (1983) studied the Hα asymmetry of the solar flares and found that, 92% of the flares studied show red asymmetry, 5% shows blue asymmetry while 3% lack of the obvious red asymmetry during some stages of their flare development.

In some cases, the blue asymmetry of Hα line profiles may also appear and persist for rather long time as shown by Heinzel et al. (1994). Fisher et al. (1985) found that, the origin of the downflows could be related to the chromospheric condensations which are believed to result from impulsive heating at the top of the chromospheres and accompany the formation of the chromospheric evaporation. Wulser (1987) stated a quantitative value of the red asymmetry by measuring the effective line width separately for the red and blue wings then subtracting the first from the later. De la Beaujardiere et al. (1992) have calculated the temporal evolution of the downward velocities and found that the slowing-down time is about four times longer than the value predicted in a theoretical model of Fisher (1989). Some detailed computations have shown a complicated correlation between the velocity field and the line asymmetry. Gan et al. (1993) 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. Heinzel et al. (1994) also found that a downward velocity in the transition region and upper chromospheres would produce a blue asymmetry of the Hα line. Asymmetric behavior of Hα foot point emission during the early impulsive phase of a flare studied by Qiu et al. (2001), shows that the asymmetric Hα foot point emission cannot be explained by the magnetic mirroring effect in which strong field foot points show lower precipitation rates. Gu and Ding (2002) found that the velocity distribution shows that, the red shift and blue shift velocities lie respectively in the northern and southern parts of the flare and that the maximum red-shift velocity is 35 km/s and the biggest blue-shift velocity is 40 km/s for Hα. Berlicki (2007) showed that the downward motion increases at the onset of a flare to its maximum velocity of 40–100 km/s shortly before the impulsive peak of microwave emission. Generally, it is difficult to infer the exact mass motion velocities of an optically thick line, especially in the case of the large velocity gradient. A relatively accurate method is to make detailed computation of the line profile from the atmosphere with the existence of various velocity fields.

3. Data used

In the present study, the Hα spectra of a weak flare on June 26, 1999 was taken by Ondrejov multichannel flare spectrograph and used during the observation time interval from 07:23:33 UT to 08:05:51 UT in the active region NOAA 8598 located at N20 E09 as shown in Fig. 1. This Hα spectrum was the only available spectra for study. According to Solar Geophysical Data, this flare began at 07:18E UT, ended at 08:19:09 D, reaching its maximum at 07:23 UT, with Hα importance SF and according to GOES, it had soft X-ray class C 7.0. The observed frames spectra involved Hydrogen Balmer lines H_α and H_β and the infrared strongest Calcium triplet line 8542 Å. The observed frame spectra have been analyzed and stored in digital form. An example is shown in Fig. 2. The registered observations of this flare are about 42 min from its beginning to its end. The three emission spectral lines (Hα, H_β and the infrared strongest Calcium triplet line 8542 Å) appeared clear. This flare is unstable with complicated morphology with good seeing and good features.

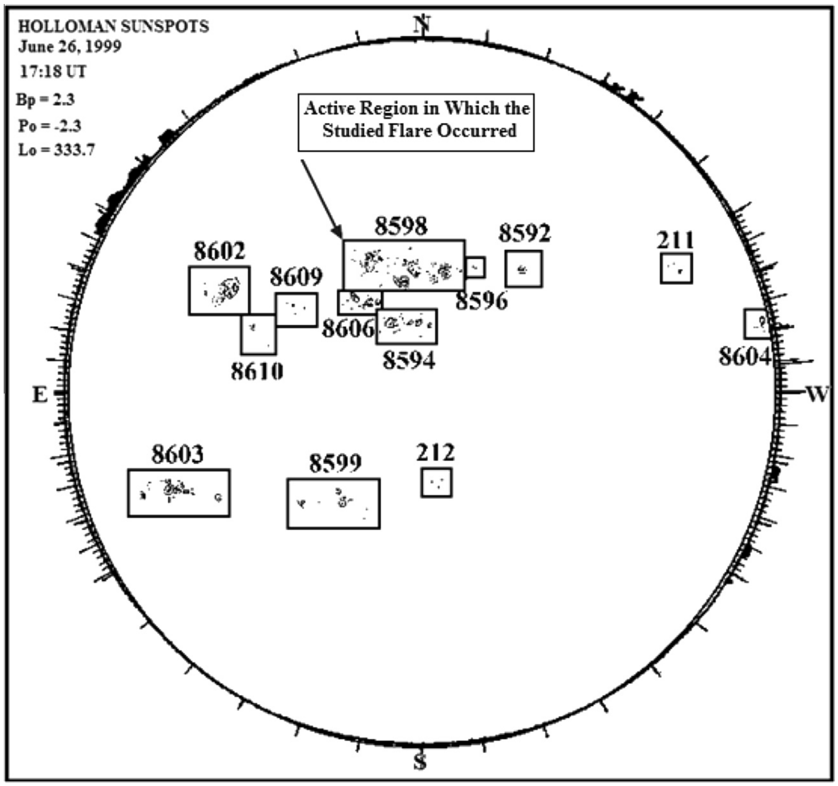

Fig. 1 Position of the flaring region of June 26, 1999 on the full solar disk according to the trace data taken in white light at 07:38:38 UT.

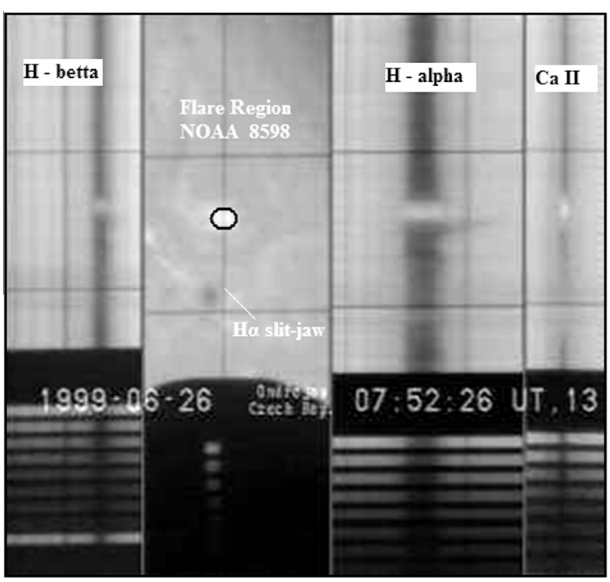

Fig. 2 The image of NOAA 8598 was taken by MFS which is composed of the H_β spectrogram, H_α slit-jaw filtergram and H_α spectrogram taken for the studied solar flare on June 26, 1999 at 07:52:26 UT, the black circle marks the kernel where the H_α line profile was obtained.

4. Asymmetry method

The Hα line profile has been widely used as a diagnostic tool for the determination of the physical conditions of the chromospheres during solar flares. The shape of the Hα line profile computed from static atmospheres depends greatly on the flare conditions (Canfield et al. (1984). Canfield and Gayley (1987) made further computation on Hα line profile from a dynamic atmosphere. In 1985, a study has been done by Fisher, Canfield, and McClymont showed that different parts of the profile response at different time scales to the flare heating. One of the most important phenomenons in Hα lines of solar flares is the red asymmetry of the profiles. Most of Hα spectra observed in flare kernels exhibit such a property. The downward velocity in a flaring region may represent an important parameter for discriminating between various energy transfer mechanisms (Fisher et al., 1985). Therefore, an adequate method used for the determination of the downward velocity is required.

In this section, the method used for derivation of downward velocity of the studied flare is that developed by Edward (2009). The method is quite simple. However one needs to be more careful when it is applied. The intent of the method is to subtract off the pre-flare contribution of the Hα line profile from the flare emission, leaving only a Doppler shift wing. This method may fail in at least two ways. So, one should be careful in applying it. The first way it might fail is if the pre-flare line is weak and the subtraction will then yield a profile which is double peaked. A second way, the method might fail is if the flare emission is optically thick, and the flare obscures the region where the pre-flare emission occurred. Then the subtraction will not reveal simply the flare emission. Therefore, the method will be successful only in the case where the flare is optically thin and occurs in the same volume as the pre-flare emission as in the case of the studied flare. If these conditions do not hold then some other more complicated modeling or resolved observation would be necessary to apply.

The idea of computation essentially depends on the existence of red asymmetries in the selected Hα line profiles after subtracting their pre-flare profiles. Then, by reversing the Hα line profile blue wing and subtracting it from the Hα line profile red wing, one can get a new profile which has unequal emission peak intensity compared with the original Hα line profile. This new one has red dominant shift as shown in Fig. 3, where the Hα red asymmetry profile is represented by the dotted line, the symmetry one by the solid line and the difference between them by the dashed line at UT of the selected profiles of the studied flare on 26 June 1999. On subtracting the wavelength of the intensity peak of the Hα line profile from the wavelength of the intensity peak of the red shifted profile one gets the Doppler shift wavelength. From Doppler shift wavelength one can compute the flare plasma velocity using the well known relation:

$$\text{Velocity}(V) = C[\text{wavelength shift } (\Delta\lambda)/\text{peak wavelength } (\lambda)]$$

$$V = C[(\Delta\lambda)/(\lambda)] \tag{1}$$

where C is the speed of light in km/s.

The values of the downward velocity are derived from Edward Schmahl's asymmetry method of the flaring region using the Hα line profiles at every time of observations for the studied flare on 26 June 1999. The time profile of the derived velocities shows sudden increase to its maximum value after 59 s from the commencement of observation time. The velocity gradually decreased with the decay phase of the flare, but their values fluctuate during the duration of the flare ranging from about 22 km/s to 35 km/s reaching its maximum at 07:24:33 UT. This result is in agreement with the values obtained by other authors such as Zarro et al. (1989), Wulser and Marti (1989), Gu and Ding (2002), Semeida et al. (2004) and Berlicki (2007).

5. Bisector method

The bisector method has widely been used for quantitative analysis of the line profile asymmetries due to the complicity of the transfer solution. It is defined as the locus of points midway between the equal points on either side of the line profile. For practical use it is usually expressed as a distance from the line center in units of velocity. Some detailed computations have shown the complicated correlation between the downward velocity and the line asymmetry. Heinzel et al. (1994) found that downward velocity in the transition region and upper chromospheres would produce a blue asymmetry of the Hα line. Gan et al. (1993) also show 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 the spectral lines (Hummer and Rybicki, 1968). This leads to say that, the bisector method fails to yield correct results in some cases. Moreover, the reliability of the bisector method changes from flare to flare, even from pixel to pixel (Ding et al., 1994). However, for the studied flare, only red symmetries of the Hα line are selected and it is assumed that the asymmetries are produced by chromopheric downward motion. So, the downward velocity values derived from the bisector method can reflect a 'mean' effect of the down flow in the line-forming region.

Generally, it is difficult to determine the exact downward velocities of the flare plasma from the asymmetries of the optically thick region. If the velocity gradient in the chromospheres is large, then the bisector method can be used, because the Doppler-shift of any bisector results from a superposition of many shifts due to the motion of plasma with different velocities along the line-of-sight (Berlicki, 2007). In the computation, the dichotomy between the flaring region and the undisturbed one is made by using the difference profile (the flare profile with subtracted preflare one) to determine the velocity. Since the different parts of the spectral line are formed at different heights in the chromosphere, using bisectors connecting the wings observed at different frequency, the line-of-sight velocity at different layers of the chromosphere can be estimated. However, because the radiation of specific frequency within the spectral line does not come from a narrow layer of the chromosphere but rather from geometrically thick region, one cannot say that the Doppler velocity determined from a given bisector correspond to plasma flow at a given height in the chromospheres. Therefore, by using the bisector method, Doppler shift of the bisector of the difference Hα profile at every time of observation is obtained.

The downward velocities corresponding to the Doppler shifts at all emission levels relative to the line center are computed, which show the difference profiles at every time of observation and the velocity derived from Doppler shift of the bisector (see Fig. 4). The temporal evolution of the average values of downward velocity derived by the bisector method for the difference profile of Hα is computed. It shows that, the downward velocity values are sharply fluctuating and in the same time they are gradually decreasing with the evolution of the flare. The velocity values are ranging from about 0.40 km/s to 6.42 km/s. These values are very small compared to the velocity values derived by asymmetry and modified the cloud model methods by factor of about 1/10. This result also disagrees with the results obtained by other authors, for example, Ding et al. (1999). The reason may be explained that, they obtained the Doppler shift of the bisector of the difference or original Hα profile for each space pixel and used critical value of the line center intensity (1.3 times the value of the quiet-sun reference profile, while in this new study, the average velocities corresponding to the Doppler shifts at all emission levels relative to the line center of every Hα profile are computed.

6. Modified cloud model method

The downward velocity is already described and used by Liu and Ding (2001a,b), Gu and Ding (2002) and Semeida et al. (2004), which is obtained from converting the Doppler shift derived by using the modified cloud model. The values of downward velocity that are computed by this method range from about 20 km/s to 44 km/s with a mean average value of about 28 km/s. This value is less than the maximum velocities obtained by Ichimoto and Kurokawa (1984), Zarro et al. (1988) and Wulser and Marti (1989), but it is reasonable and in good agreement and comparable with those of Canfield et al. (1990a,b), Wulser et al. (1992), Ding et al. (1995), Liu and Ding (2001a,b), Gu and Ding (2002), Semeida et al. (2004) and Berlicki (2007). The evolution of the downward motions increased very fast during the first 3 min reaching its maximum velocity at 07 26 22 UT. Then it suddenly decreased

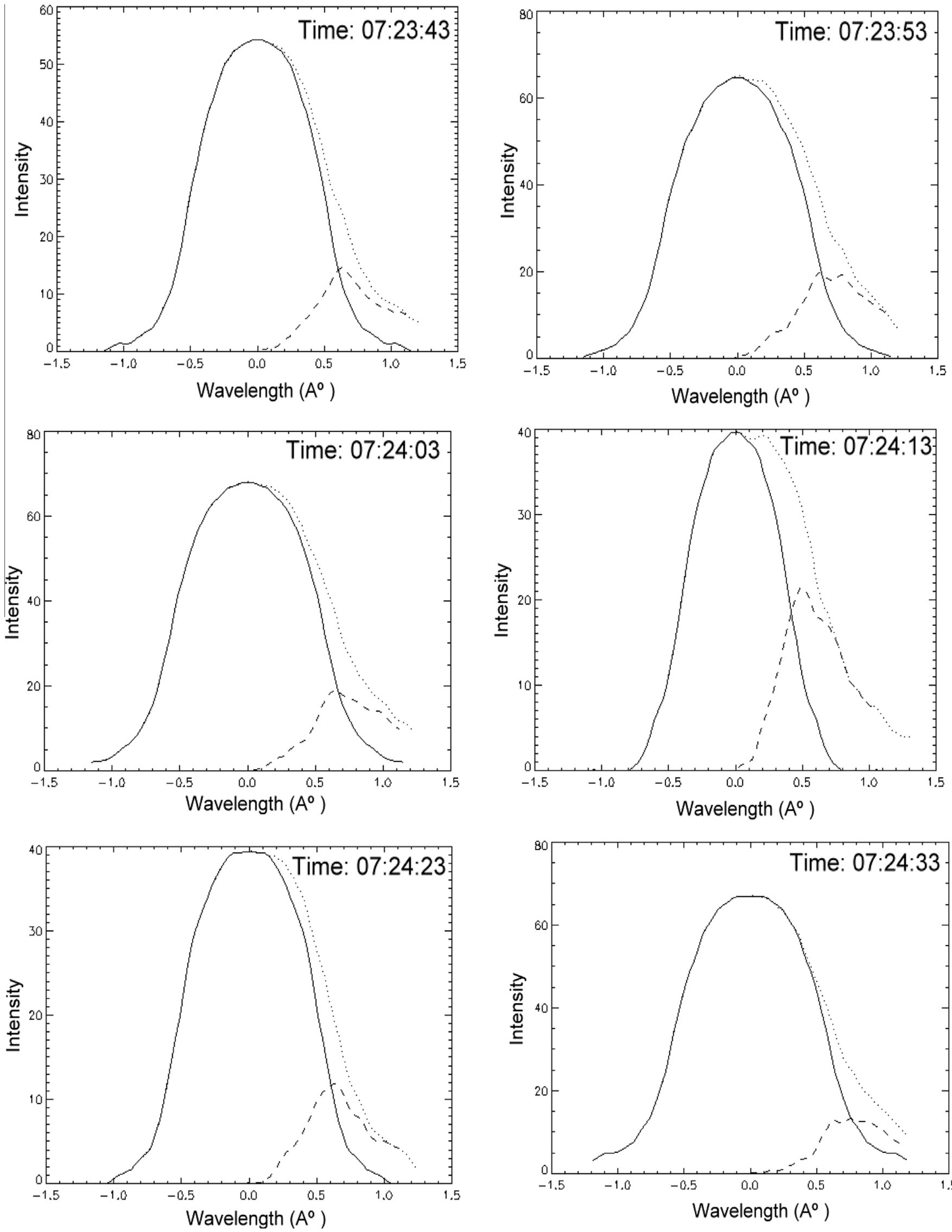

Fig. 3 The Hα red asymmetry profiles (dotted line), its symmetry one (solid line) and the difference between them (dashed line) at times 07:23:43 UT, 07:23:53 UT, 07:24:03 UT, 07:24:13 UT, 07:24:23 UT and 07:24:33 UT respectively for the flare on 26 June 1999. Line intensity is in units of $I_{\text{continuum}}$.

by about 18 km/s. The downward motions started again slightly fluctuating for the next 20 min. Finally, it is gradually decreased with decreasing the maximum intensity of the H_α line emission. The result is consistent with previous observations (e.g. Ding et al., 1995; Liu and Ding, 2001a,b). This has been interpreted as a result of superposition of several condensations within an unresolved region (Fisher, 1989). Wang et al. (2001) showed in their study that the emission in the wings of H_α line profile could also exhibit high frequency fluctuations which was interpreted as a signature of fine structures

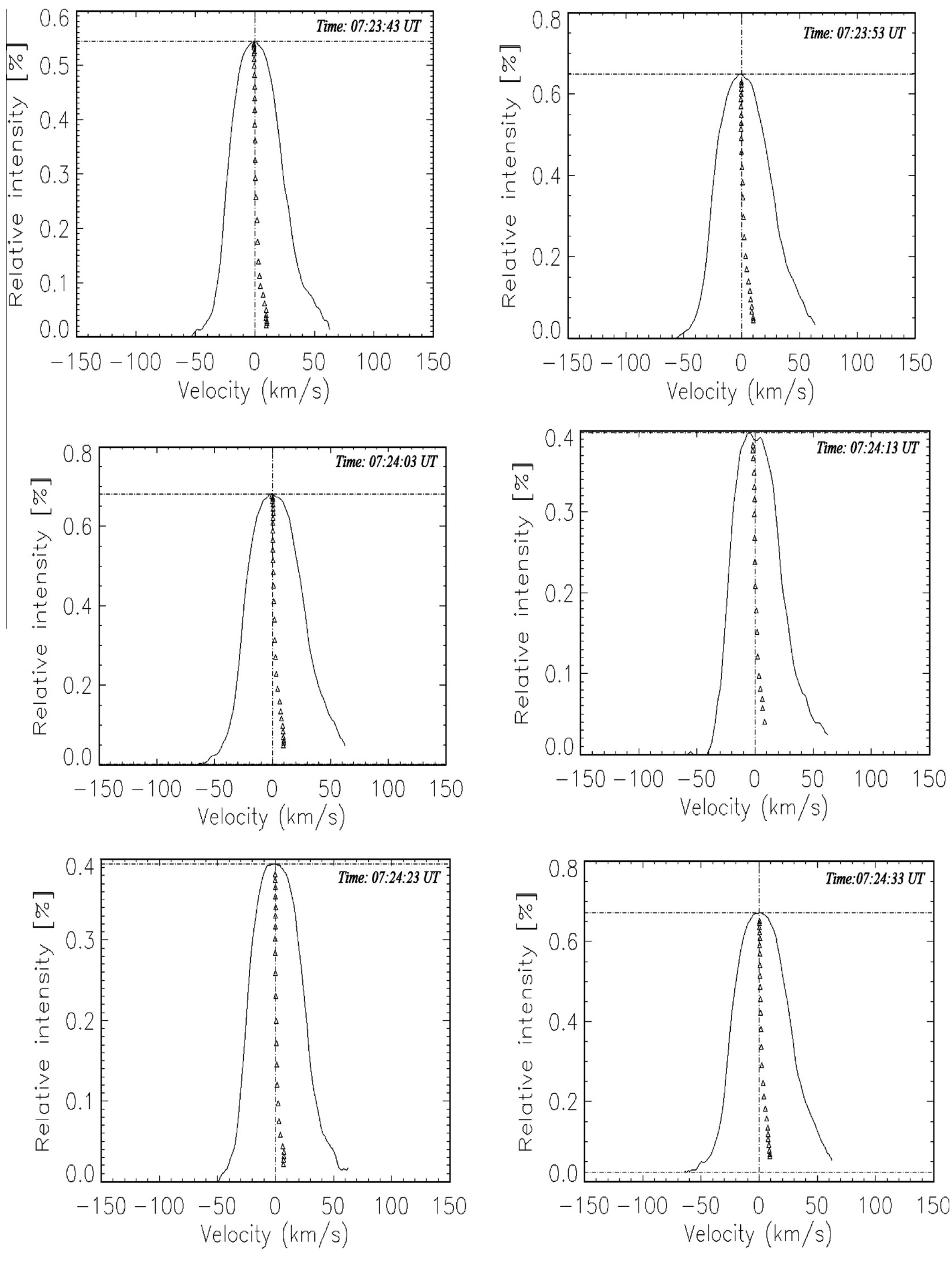

Fig. 4 The difference profiles (solid line) and the velocity derived from Doppler shift of the bisector (triangle line) at times 07:23:43 UT, 07:23:53 UT, 07:24:03 UT, 07:24:13 UT, 07:24:23 UT and 07:24:33 UT respectively for the studied flare on 26 June 1999. Line intensity is in units of $I_{continuum}$.

related to elementary bursts; thus, the net line emission and downward velocity derived from the line could be fairly large even in the later phase (Ding et al. 2001).

7. Conclusion

Three methods have been used to compute the downward velocity for the studied flare of June 26, 1999. The asymmetry method is used to determine the plasma downward velocity of the flare from the Hα line asymmetries by subtracting the preflare profile from Hα line profile, while the modified cloud model method is used to obtain the downward plasma velocity of the flare without subtracting the preflare profile from Hα line profile. Although, the bisector method has been widely used for quantitative analysis of line profile asymmetries, this method fails to yield the correct results in some special cases.

The bisector method used here to test its validity for computing the downward plasma velocity of the studied flare.

By a comparison between the three downward velocities obtained by the three methods, one can extract the following comments:

- Though these figures show a difference between the downward velocities obtained from the three methods, but in general they are correlated with each other and have almost the same trend. In particular, there is a noticeable strong correlation between the downward velocities determined from the asymmetry method and modified cloud model methods which reveals that these two methods have the same validity to compute the chromospheric velocity indicated by the Hα line asymmetries of the flaring region.
- All of them show fluctuations in the downward velocity values throughout the duration of the flare. These fluctuations in chromospheric plasma velocity reflect the fluctuations in the maximum intensity of Hα line profiles. Therefore, the Hα line of the solar flare is very sensitive to flare activity and it is important to explain the intensity change during the whole life of the flare in order to discriminate the effects of nonthermal particles, conduction and irradiation due to X-ray flux.
- The downward velocity values obtained from both asymmetry and modified cloud model methods are very close ranging from 20 km/s to 44 km/s and consistent with previous results (e.g. Wulser and Marti (1989), Zarro et al.(1989), Ding et al.(1995), Liu and Ding (2001a,b), Gu and Ding (2002), Semeida et al. (2004) and Berlicki (2007). They reach their maximum values at different times. The maximum downward velocity in the asymmetry method was at about 07:24:33 UT, while in the modified cloud model method it was at about 07:26:22 UT. In the case of the bisector method, the maximum downward velocity was at about 07:26:34 UT.
- The downward velocity values computed from the bisector method is ranging from 0.42 km/s to 6.42 km/s, very far from those obtained by other two methods and disagrees with the above mentioned results with the previous studies such as Ding et al. (1999).

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