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LETTER

Letter to the Editor

Multi-line two-dimensional spectroscopy of a limb flare

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Abstract. We present the result of a preliminary analysis of the 2D spectra of Hα and Ca II $\lambda 8542$ for a limb flare on 11 November, 1998. Near the top of the flaring loop, the Hα line is extraordinarily broadened. The effect of line opacity (or the saturation of line core) cannot fully account for the observed line width since it requires an extremely high loop density ($n_{\rm H} \gtrsim 10^{13}$ cm^{-3} when $T = 10^4$ K). The remaining possibility is the broadening by micro-turbulence or inhomogeneous mass motions. Since the two lines demonstrate different broadening effects, it is quite possible that they are formed in different fine structures which cannot be spatially resolved by observations.

Key words: line: profiles – Sun: flares – Sun: prominences

1. Introduction

Modern observations have revealed that solar flares are loop phenomena. Traditionally, flares are thought to fall into two classes: dynamic (two-ribbon) and confined (simple-loop) flares. Dynamic flares can be well explained by the so-called Kopp-Pneuman model (Kopp & Pneuman 1976). According to this model, dynamic flares proceed with the reconnection of opened magnetic field lines, which results in a series of loops. The outermost loop is newly created through magnetic reconnection and contains hot plasma that emits soft X-ray radiation. The innermost loop, regarded as the aftermath of outer hot loops, is relatively cool and visible in Hα. Such cool loops are also known as post-flare loops. On the other hand, confined flares are believed to occur through the interaction of a pre-existing loop with an emerging magnetic flux. Quite recently, Shibata (1998) proposed to unify these two kinds of flares into a common reconnection model. Chen et al. (1999) further showed through numerical simulations that their different features may be simply due to their different altitudes of reconnection site (magnetic neutral point), that is, dynamic flares are likely to occur higher than confined flares.

The nature of post-flare loops in dynamic flares has been an attractive subject for quite a long time. For example, based on spectral observations in both Hα and soft X-ray, Schmieder et al. (1995, 1996), Wiik et al. (1996), and van Driel-Gesztelyi et al. (1997) made extensive studies on the post-flare loops of 26 June, 1992 and obtained the physical parameters of the loops such as the temperature, density, emission measure, cooling time, and mass flow velocities. In particular, Malherbe et al. (1997) found that the velocities near the top of loops are close to free-fall motions but are much smaller at the loop footpoints, implying a deceleration process. Heinzel et al. (1992) have proposed that the temporal variation of the magnetic loop geometry, the helical structure of magnetic field, and the inhomogeneity of the falling plasma might be the cause of such a deceleration process. Helical motions inside the loops can also lead to a broadening of spectral lines (e.g., Heinzel et al. 1992).

Theoretically, if magnetic reconnection occurs at a lower level, as in the situation which Chen et al. (1999) used to explain confined flares, the flaring loop has a higher mass density and accordingly a shorter radiative cooling time. One expects that in this case, the evolution of the flaring loop is fast, making hot and cool plasmas more spatially correlated than in the case of dynamic flares. However, this point needs to be checked by observations.

Recently, Mein et al. (1997) made 2D spectroscopy of a disk flare at Hα and Ca II $\lambda 8542$ lines. In particular, they suggested that a magnetic reconnection at chromospheric levels could explain the characteristics of line asymmetries. Using the imaging spectrograph at the solar tower of Nanjing University (Huang et al. 1995), we have observed an off-limb flare on 11 November, 1998 at the same two lines. Line profiles were obtained for an area covering a flaring loop. In this *Letter*, we investigate preliminarily the line broadening within the loop and discuss its possible explanations.

2. Observations and data reduction

The flare to be analyzed occurred at the northwest limb (N25 W86) on 11 November, 1998. According to the *Solar Geophysical Data*, the flare started at 02:10 UT, peaked at 02:15 UT, and ended at 02:18 UT. The Hα/soft X-ray importance is SF/C3.2. In Hα, this event was characterized by the formation of a flaring loop above the solar limb.

The imaging spectrograph at the solar tower of Nanjing University can record 2D spectra of the solar phenomena at multi-

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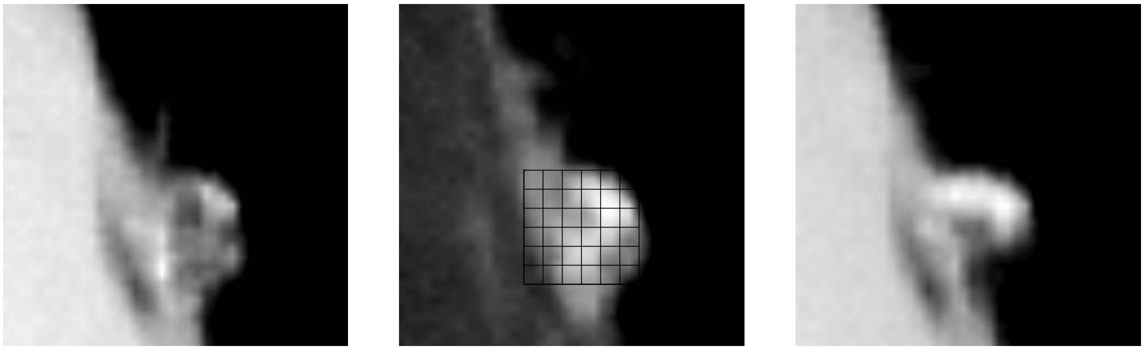

Fig. 1. Monochromatic images of Hα reproduced from the 2D spectra at 02:14:38 UT. From left to right, the three panels correspond to images at $\Delta\lambda = -2$, 0, and 2 Å, respectively. The field of view is $60'' \times 60''$. Line profiles are displayed in Fig. 2 for a small area covering the flaring loop, as delineated in the middle panel

lines using a scanning technique (Huang et al. 1995; Ding et al. 1995). In early 1998, we upgraded some optical instruments including the grating. At present, the Hα line in the second order and the Ca II $\lambda8542$ line in the first order are used. During the flare, we repeated 36 scans over the flaring area in these two lines, covering a time period from 02:00 to 02:22 UT. (Note that the scans prior to 02:10 UT were made for an earlier flare close to this event.) Each scan resulted in two 3D data arrays, one for each line. There are 70 pixels with a spacing 1.″5 along the slit and 40 pixels with a spacing 2″ along the scanning direction. At each spatial point, the spectrum contains 180 wavelength pixels with a spectral resolution of 0.04 and 0.10 Å pix^{-1} for the Hα and Ca II $\lambda8542$ lines, respectively. Note that during the observations the seeing was about 2″–3″ and that the CCD cameras were not saturated.

The data reduction includes dark current subtraction and flat field correction for the CCD cameras. In this *Letter*, we study the scan at 02:14:38 UT, corresponding to the Hα maximum. Fig. 1 shows monochromatic images at the Hα line ($\Delta\lambda = -2$, 0, and 2 Å) reconstructed from the 3D data array. Our purpose here is to analyze the spectra within the flaring loop shown in the figure. To do so, we delineate in Fig. 1 a squared area for which the line profiles are displayed in Fig. 2. In some positions, especially near the top of the flaring loop, the Hα lines are very broad. The wavelength window selected in the observations seems too narrow to include the whole profile. However, one can still estimate the line width based on one wing of the profile.

3. Line broadening mechanisms

We now discuss the possible causes that can result in the very broad Hα line at the top of the flaring loop. The contribution of instrumental broadening can be ruled out first. We have found that the narrowest metallic line near the present wavelength windows has a Gaussian width of $\lesssim 3\,\mathrm{km\,s^{-1}}$. Compared with other broadening sources, the instrumental broadening has therefore negligible effect on the line widths observed in this flare.

A careful scrutiny of Fig. 2 indicates that the Hα and $\lambda8542$ lines have quite different spectral features. This is first shown from their different widths. For instance, the broadest line of Hα in Fig. 2 (see the thick box) has a full width at half maximum as large as $\Delta\lambda_{\mathrm{FWHM}}(\mathrm{H}\alpha) \approx 6.5$ Å; while the $\lambda8542$ line at the same position shows only a value of $\Delta\lambda_{\mathrm{FWHM}}(\lambda8542) \approx 1.9$ Å. If these two lines were optically thin and the Doppler effect were the only broadening source, their Doppler widths are computed as $\Delta\lambda_{\mathrm{D}}(\mathrm{H}\alpha) = \frac{1}{2}\Delta\lambda_{\mathrm{FWHM}}(\mathrm{H}\alpha)/\sqrt{\ln 2} \approx 3.9$ Å and $\Delta\lambda_{\mathrm{D}}(\lambda8542) \approx 1.1$ Å. Since the temperature of the loop plasma emitting these lines is in the order of 10^4 K, the two Doppler widths would require nonthermal turbulent velocities of about 180 and $40\,\mathrm{km\,s^{-1}}$, respectively. This apparent discrepancy implies that the two lines are broadened by different mechanisms or are formed in quite different circumstances.

On the other hand, the observed profiles of $\lambda8542$ within the loop are well Gaussian-shaped, which means that the Doppler effect is the main broadening mechanism for this line. The profiles of Hα, however, deviate significantly from a Gaussian shape, implying that other broadening factors may also play a role. In fact, if the physical parameters of the flaring loop, such as its geometric size, density, and temperature, are within the ordinary range, the $\lambda8542$ line can be considered optically thin along the line of sight. The optical thickness for the Hα line varies depending on the loop parameters. In our case, the core of Hα near the loop top is almost saturated, suggesting that the line core is optically very thick.

Based on the above arguments, we first check the role of line opacity. To this end, we model the flaring loop as a uniform slab with a geometric thickness L, temperature T, hydrogen number density n_{H}, and micro-turbulent velocity v_t. Theoretically, the emission at far wings can be enhanced by simply increasing the mass density of the slab; in the case that the line core is saturated, the enhanced intensity at far wings contributes to the broadening of the line. We have made non-LTE computations for a model slab in which $L = 3000$ km (a value comparable to the diameter of the loop), $T = 10^4$ K, and $v_t = 10\,\mathrm{km\,s^{-1}}$, while n_{H} is taken as a free parameter. We find that, for an Hα line broadened by Doppler effect, radiative damping, and Stark effect, the hydrogen number density should be extremely high ($n_{\mathrm{H}} \gtrsim 10^{13}\,\mathrm{cm^{-3}}$) in order to produce the required line width.

In fact, the loop density can be determined by fitting the absolute line intensities. Through tentative computations, we obtain a mean value of n_{H} no greater than 5 $10^{12}\,\mathrm{cm^{-3}}$ when other

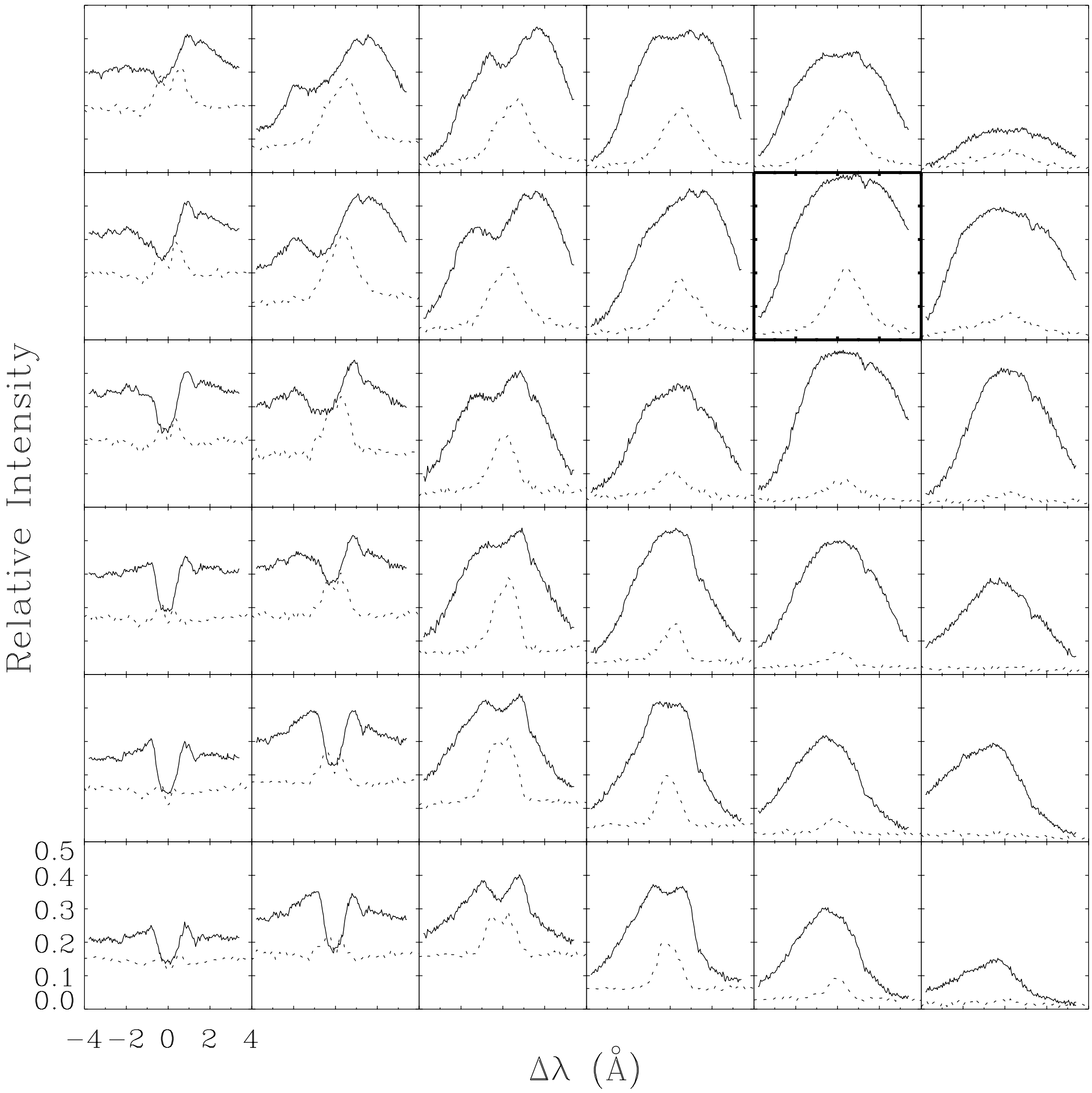

Fig. 2. Line profiles of Hα (solid lines) and Ca II λ8542 (dashed lines) at 02:14:38 UT. The units of intensities are arbitrary. The thick box refers to the broadest Hα line in this figure. Each box has a one-to-one correspondence to each small square shown in the middle panel of Fig. 1

loop parameters are specified as above. Therefore, although the effect of line opacity cannot be excluded, it seems unlikely to be the main contributor to line broadening.

We suggest that the line broadening is mainly due to micro-turbulence and/or inhomogeneous macroscopic mass motions. As stated above, the Hα and λ8542 lines demonstrate different broadening effects. This would be a consequence when the loop contains fine structures along the line of sight or in a spatially unresolved area. The two lines may be formed in fine structures with quite different physical parameters.

The above argument is supported by the fact that the emission of Hα and that of λ8542 depend in different ways on the loop temperature. To check this point, we have further made non-LTE computations for one-dimensional model slabs vertically standing on the solar surface. The disk radiation, incident on both sides of the slab, is computed from the F1 flare model (Machado et al. 1980) and diluted by a factor of 0.5. We take the geometric thickness of the slab as $L = 3000$ km, the hydrogen number density as $n_{\rm H} = 10^{11}$ cm^{-3}, and vary the slab temperature. The wavelength-integrated intensities of the two lines emergent normally from the slab surface are then computed and plotted in Fig. 3 against the slab temperature. It clearly shows that the emission at Hα peaks at a higher temperature than that at λ8542.[1] Thus, if larger turbulent velocities exist preferentially in hotter plasma, different broadening effects will naturally appear in the two lines. The cause of such temperature-dependent velocities may be related to the magnetic reconnection process that leads to the formation and the heating of the flaring loop.

[1] In the computations, we have not included a macroscopic velocity field within the slab, which can cause an effect of Doppler-brightening or Doppler-dimming for the lines (Heinzel & Rompolt 1987), thus changing somewhat the temperature dependence of the line intensities.

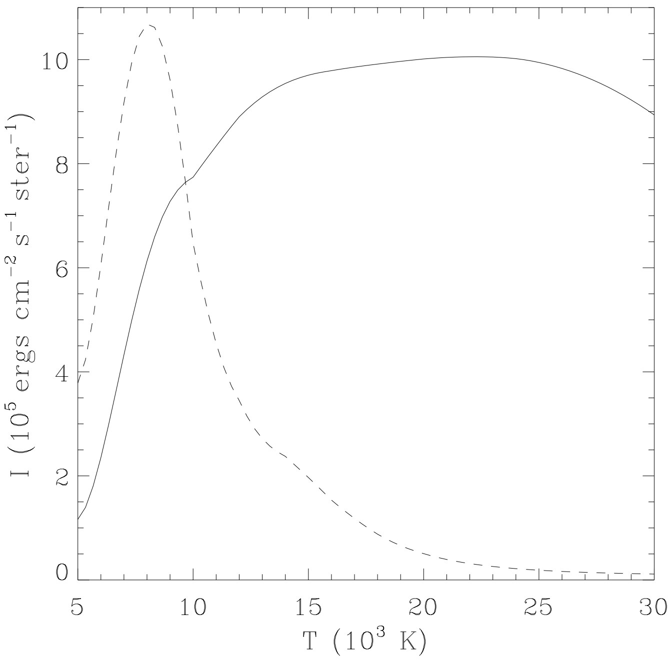

Fig. 3. Wavelength-integrated intensities of Hα (solid curve) and Ca II $\lambda 8542$ (dashed curve) emergent normally from model slabs in dependence of the slab temperature. The latter curve has been multiplied by a factor of 180. The slab thickness is set to be $L = 3000$ km and the density to be $n_{\rm H} = 10^{11}$ cm^{-3}

4. Conclusion

We have analyzed preliminarily the 2D spectra of Hα and Ca II $\lambda 8542$ for a limb flare on 11 November, 1998. The Hα line profiles near the top of the flaring loop are shown to be extraordinarily broadened. The effect of instrumental broadening can be excluded because of the narrowness of observed metallic lines. For a uniform loop model, the effect of line opacity, i.e., saturation of line core, cannot fully account for the observed Hα line width since it requires an extremely high loop density ($n_{\rm H} \gtrsim 10^{13}$ cm^{-3} when $T = 10^4$ K).

We suggest that micro-turbulence and/or inhomogeneous mass motions are the main cause of line broadening. The fact that the observed profile of Hα suffers a greater broadening effect than that of $\lambda 8542$ implies the existence of different fine structures along the line of sight or in a spatially unresolved area. Non-LTE computations have shown that the Hα line is formed in a hotter plasma than the $\lambda 8542$ line. Thus, a favorable situation is that larger turbulent velocities are confined to hotter fine structures while smaller velocities to cooler ones.

As mentioned in Sect. 1, a low-lying flaring loop shows signatures of a high mass density and possible coexistence of hot and cool plasmas. The above conclusion implies that the characteristics of the flare on 11 November, 1998 are roughly compatible with such a scenario. The temporal evolution of this flare will be discussed in our later work.

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