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Hα Line Polarization in the 2B/X4.8 Flare of 2002 July 23 *

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Abstract On 2002 July 23, a 2B/X4.8 flare was observed in the Hα line spectropolarimetrically by the Large Solar Vacuum Telescope of Baikal Astrophysical Observatory. Linear polarization of 3%–10% was detected in the Hα line, particularly where the line showed central reversal. The linear polarization is mainly radial on the solar disk and appears at the impulsive phase of the hard X-ray and γ-ray bursts. It is limited to some relatively small regions of the flare. The polarization in a limited small region ($\sim 4'' - 5''$) changed its direction within a short period of time ($\sim$ 10s).

Key words: Polarization — line: profile — Sun: flare

1 INTRODUCTION

As is well known, energetic particles, mainly electrons and protons, can be accelerated in the solar atmosphere when there is a sudden energy release, such as in a magnetic reconnection and/or shock waves etc. In the solar flares, protons of energies more than 1 MeV can be detected by their γ-ray line emission, while the non-thermal electrons of energies more than 10 keV can be diagnosed by their X-ray and radio emission. Electrons with high energies can also be detected by X-ray line polarization and γ-ray continuum. Although the relative contributions of electrons and protons to the solar flare energy budget are, so far, not well known, non-thermal protons of energies below 1 MeV could play an important role in the energetics of solar flares (Emslie et al. 2000). Moreover, there exists presumably magnetic reconnection in the lower solar atmosphere (e.g. Chen et al. 2001; Ji & Song 2001; Fang et al. 2002; Fang et al. 2003a), which can provide energetic particles necessary to account for the Type II white light flares and Ellerman bombs (Ding et al. 1998).

Thus, how to detect energetic particles in the chromosphere is an important subject. Recent studies show that the low energy protons and electrons can be diagnosed by use of UV and optical spectra of solar flares (see, e.g. Hénoux & Fang 1996; Fang et al. 1996; Fang et al. 2000; Fang et al. 2003b). Among several useful methods, one is the linear polarization measurement

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of chromospheric lines caused by energetic particle impact (Hénoux et al. 1990; Kazantsev & Hénoux 1995; Hénoux & Vogt 1998). It has been shown that the observed polarization degree and direction depend on the type of exciting particles and the energy, as well as on the angular distributions of the particles (Voget & Hénoux 1996; Emslie et al. 2000). In a vertical guiding magnetic field, particles of energies $E < E_0$ will produce a polarization vector along the radial direction on the solar disk, while particles with higher energies correspond to a polarization vector in the tangential direction. The "crossover" energy E_0 is about 200 eV for electrons and 200 keV for protons (Voget & Hénoux 1996). Several reports indicated the existence of linear polarization in Hα lines from Lyot filter measurements (Hénoux et al. 1990; Vogt & Hénoux 1996) or spectropolarimetric observations (Firstova et al. 1997; Hénoux et al. 2003a; Hénoux et al. 2003b). In particular, Hénoux et al. detected in the flare of 1982 July 11, a degree of polarization of about 1%–2%; Vogt et al. found the flare of 1989 June 20 to have a degree of polarization exceeding 5%. All these flares were observed with a flare patrol heliograph equipped with a Lyot filter. At the same time, multi-line spectropolarimetric observations were made for a few flares by THEMIS or some other similar telescopes (e.g. the Large Solar Vacuum Telescope of Baikal Astrophysical Observatory described below in detail). Recent results from Hénoux et al. (2003b) showed that the degree of polarization reached 4% in the Hα line for the flare of 2001 June 15 observed by THEMIS. It is worth noting that optical spectropolarimetry has several advantages: it can eliminate the effect of Doppler motion on the filter observations and the profiles can provide complementary information on the mechanisms of energy transportation and deposit in the solar atmosphere (Fang, Hénoux & Gan 1993; Hénoux, Fang & Gan 1993).

On 2002 July 23, a 2B/X4.8 flare was observed in the Hα line by spectropolarimetric method using the Large Solar Vacuum Telescope of Baikal Astrophysical Observatory. This flare was also observed by RHESSI, TRACE and some other ground-based instruments. It provides a good opportunity to study the non-thermal particles and the energy transportation and deposit in solar flares. The present paper gives our detailed results of the spectropolarimetric measurements and preliminary results of a multi-wavelength analysis.

In Section 2 we summarize the observations. The results of the data analysis will be given in Section 3. Section 4 contains a discussion and the conclusions reached.

2 SPECTROPOLARIMETRIC OBSERVATIONS

On 2002 July 23, a major 2B/X4.8 flare occurred at S13E72 on the solar disk. According to SGD report, it began at 00:15 UT, reached maximum at 00:35 UT and ended after 02:00 UT. Spectropolarimetric observations of the Hα line of the flare were made using the Large Solar Vacuum Telescope of Baikal Astrophysical Observatory, affiliated with the Russian Institute of Solar and Terrestrial Physics. The telescope is an one-mirror tracking system with a polar siderostat located on a 25 m high metal column. Sunlight is reflected along the polar axis direction to a crown-flint doublet objective lens with an aperture of 76 cm and a focal length of 40 m. The sunlight passes through sealed glass windows to illuminate the spectrograph and a birefringent filter, which is centered at the Hα line (Skomorovsky & Firstova 1996). The solar image at the spectrograph entrance slit rotates one complete turn in 24 hours. The basic parameters of the instruments are listed in Table 1. The observation was made from 00:32:09 to 02:55:45 UT. Figure 1 shows a Hα image of the flare, obtained at BBSO, with the orientation and the position of the spectrograph entrance slit at the beginning of the observation. From

Fig. 1 we can see there are two ribbons in this flare region — an east and a west one. Figure 2 depicts the evolution of hard X-ray (from RHESSI) and radio bursts (from the Nobeyama radioheliograph and Huairou station of the National Astronomical Observatory in Beijing) in the early phase of the flare. Dashed lines show the main period of time when the linear polarization was detected (see below). The start time of observation is also indicated in this figure.

Table 1 Observation Parameters

Items	Parameters
Spectrograph slit width	70μm $= 0.35''$
Spectrum order	2nd left
Dispersion	0.6Å/mm=0.013 Å/pixel
Spectral resolution	0.014 Å
Height of one spectrum band	$30'' = 176$ pixel
Exposure time	0.1 s
CCD spectrum detector	TEK 512 $\times$ 512

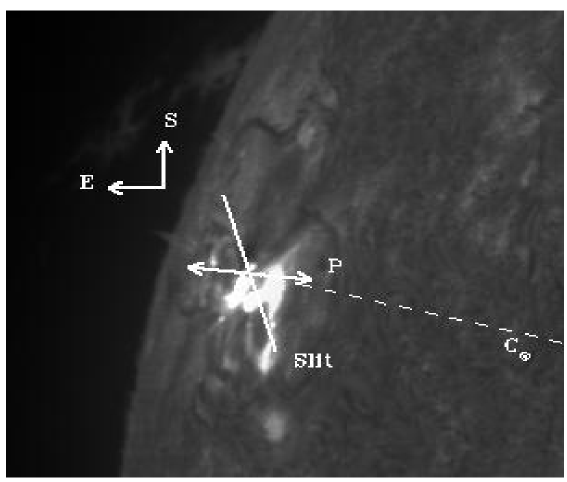

Fig. 1 Hα image of the solar flare, obtained at BBSO, with the position of the spectrograph entrance slit at the beginning of the observation. The dashed line orientates the solar disk center ($C_{\odot}$). The average angle between the polarization(P) and the flare-to-disk center directions is 9°. East is to the left and South is up.

The linear polarization observations were made using a Wollaston prism mounted behind the entrance slit of the spectrograph. A rotating achromatic half-wave plate is put in front of the slit to determine the orientation of the polarization vector. Linear polarization parallel or perpendicular to the entrance slit direction was extracted from the observations made with this half-wave plate. The upper (lower) spectral band corresponds to the polarization parallel (perpendicular) to the entrance slit. These two bands provide the Stokes parameter Q. By turning clockwise the half-wave plate by 22.5°, the two spectral bands give the linear polarization oriented at 45° angle with respect to the direction of the entrance slit, i.e. the Stokes parameter U. A second half-wave plate is inserted behind the Wollaston prism to align the oscillation direction of the electric vector in the ordinary and extraordinary beams at 45° angle with respect to the grooves of the grating. This plate, in the absence of the first one, was adjusted by equalizing the quiet-Sun intensities in the two spectral bands. This is important since the instrumental polarization changes during the day due to the rotation of the solar image. Thus, using the second half-wave plate practically removes the influence of the instrumental polarization.

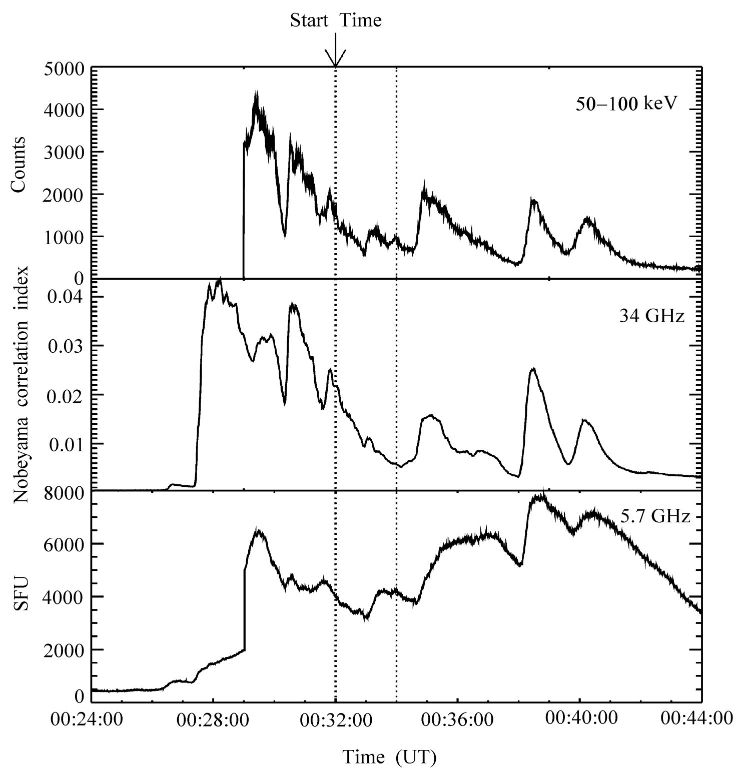

Fig. 2 Time evolution of hard X-ray (from RHESSI) and radio bursts (from Nobeyama radioheliograph of NAOJ and Huairou station of the National Astronomical Observatory in Beijing) in the early phase of the flare. Dashed lines show the main time period when linear polarization was detected. The start time of the observation is also indicated.

3 DATA ANALYSIS

During the observations 247 spectrograms of the Hα line were obtained. Figure 3 shows several original CCD spectral images during the flare development. At the beginning of the observations the time interval between exposures was 6–10 s.

The intensity profiles I(up) and I(down) in the two spectral bands were measured along the dispersion direction, averaged over every 3 pixels. In order to eliminate the effect of possible residual instrumental polarization, all intensities were normalized relative to the intensity of the continuum. Since the profiles do not reach the real continuum, we used the intensities at $\pm$4.5Å, of a quiet-Sun Hα profile for the calibration.

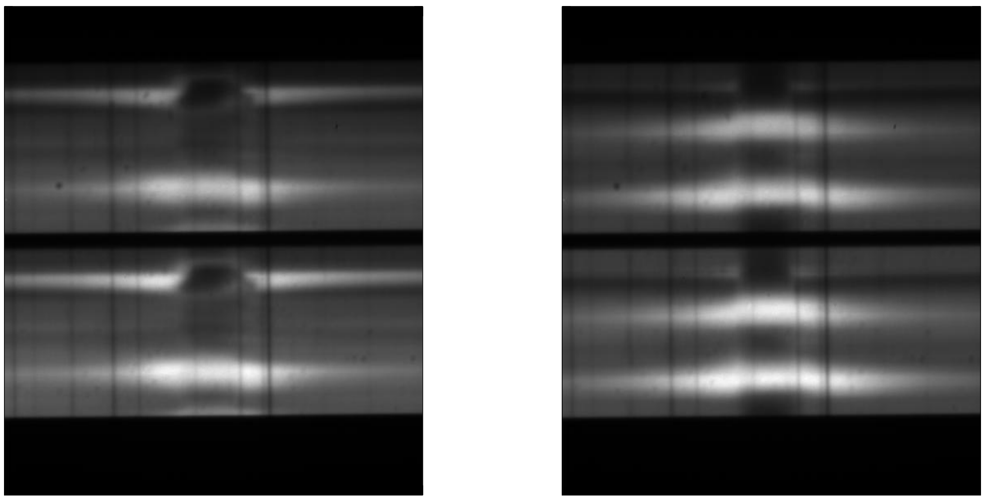

Fig. 3 Several original CCD — images during the flare development.

Table 2 Temporal Variation of the Maximum Values of the Stokes Parameters

Number of frames	time (UT)	Stokes parameters
1	00: 32: 09	$Q = -0.050$
2	00: 32: 20	$Q = -0.100$
3	00: 32: 27	$Q = -0.047$
4	00: 32: 38	no polarization
5	00: 32: 48	no polarization
6	00: 33: 00	$U = -0.075$
7	00: 33: 06	$Q = -0.030$
8	00: 33: 14	$U = -0.067$
9	00: 33: 33	no polarization
10	00: 33: 44	no polarization
11	00: 33: 53	$Q = -0.088$
12	00: 33: 59	$U = -0.058$

If the polarization degree is less than 2%, we regard it as no polarization.

Twenty frames, particularly those during the flare impulsive phase, have been analyzed, and 47 Hα profiles have been obtained. It was found that among the 47 profiles, polarization can be detected only in those with central reversal. Some examples of the observed spectral profiles in the up (solid lines) and down (dashed lines) bands are given in Fig. 4. In the figure, the Stokes parameters $Q(U)/I = (I(\text{up}) - I(\text{down}))/(I(\text{up}) + I(\text{down}))$ are also plotted. It shows that the instrumental polarization in our observations does not exceed 2%. In Fig. 4, the left four panels indicate the absence of polarization, and the right two panels show presence of non-zero Stokes parameters; the latter were mainly obtained in the Hα line profiles with central reversal of the east flare ribbon.

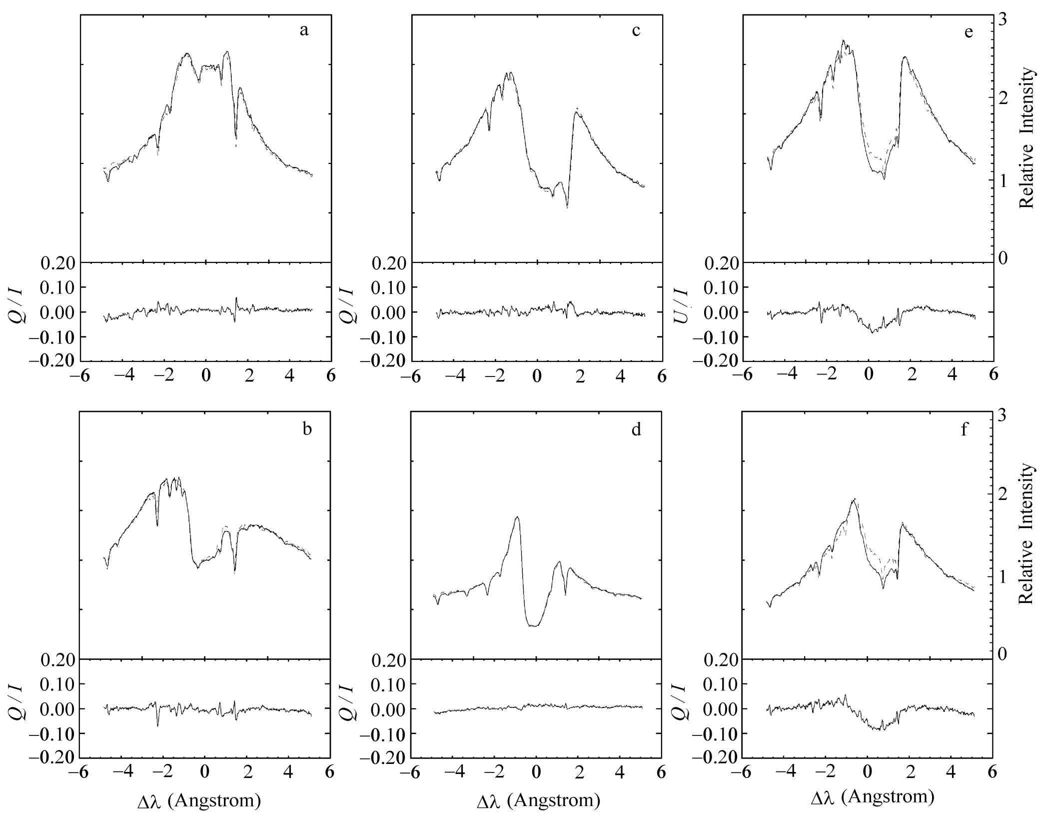

Fig. 4 Several Hα line profiles in the up spectral band (solid lines) and the down band (dashed lines), showing some of them without polarization (a, b, c and d), and some with polarization (e and f).

The polarization was absent after 00:34 UT (N12). Table 2 summarizes some numerical results of the spectropolarimetric observations, some of them (e.g. 4, 5, 9, 10) show no distinct polarization and their Hα profiles present no central reversal. From the table, the variation of the maximum values of the Stokes parameters can be clearly seen. We paid more attention to N1 and N2 frames obtained in an earlier phase of this flare. Figure 5 presents the Q Stokes parameters in several profiles on the frames N1 (left column) and N2 (right column). The distance between the positions of each profile along the entrance slit is about $0.5''$. It shows that the behavior of the Q-profiles in the frame N1 changes both along the positions of the slit and along the dispersion direction. In the first profile of the frame N1 the polarization is positive, while in the last profile it becomes negative. There is an interesting and unknown large gap in the position near –0.5Å. In several last profiles of the frame N2 a negative polarization is convincing, but in the second and third ones there are weak positive Q-Stokes parameters. This indicates a change in the direction of the polarization within a spatially limited region of the flare ($4'' - 5''$) and within a time period of 10 s.

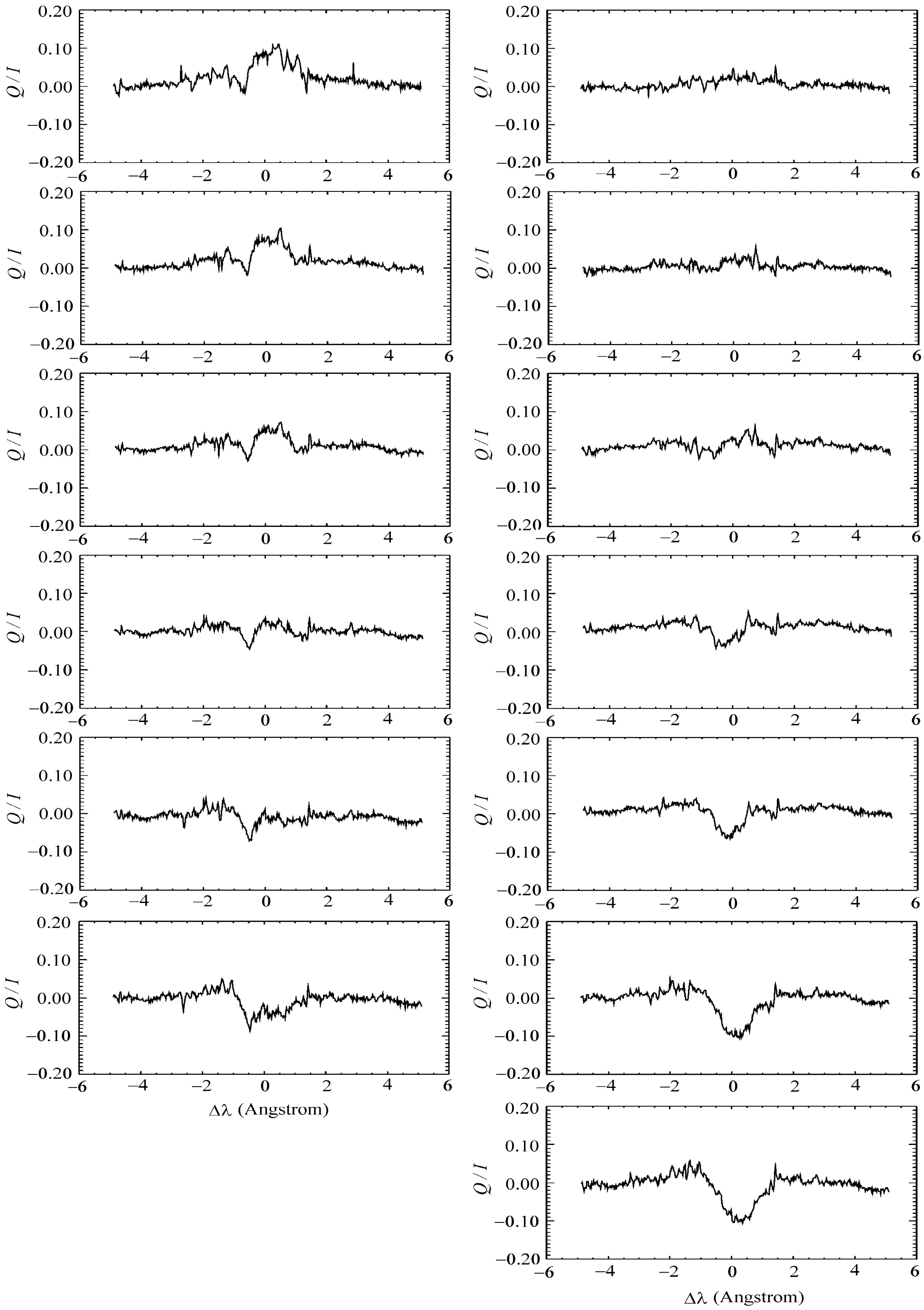

Fig. 5 Stokes parameter Q in several profiles on the frames N1 (left) and N2 (right).

The degree of polarization P and the azimuth of polarization relative to the direction of the entrance slit, χ, are given, respectively, by the formulas

$$P = \sqrt{\left(\frac{U}{I}\right)^2 + \left(\frac{Q}{I}\right)^2},$$

$$\chi = \frac{1}{2}\arctan\frac{U}{Q}.$$

We evaluated the P and χ of frames N1–N12, and the results are listed in Table 2. In these frames, several profiles obtained with an interval of $1'' - 3''$ indicate absorption in the Hα line center and non-zero Stokes parameters. Figure 6 shows the definition of the polarization in our observation. For all the frames, the average P, averaged over a limited spatial region $(4'' - 5'')$ and over a short time interval (2 minutes), is 9.8%, and the similarly averaged χ is 112°. The average angle between the polarization and the flare-to-disk-center direction, $\chi_\odot$, is about 9°. The angle between the spectrograph entrance slit and flare-to-disk-center direction, α, is 59°. Therefore, for most of the cases with negative Q and U, the vector of the polarization is close to the flare-to-disk-center direction. We estimated that the precision of the degree of polarization is about 2% and that of the direction of the polarization vector is about 5°.

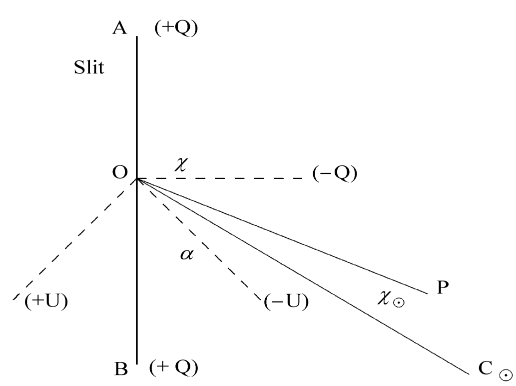

Fig. 6 Definition of the direction of Stokes parameters in our observation. AB represents the slit position and $OC_\odot$ is the direction towards the center of solar disk, χ is the angle between AO and OP and α is the angle between OB and $OC_\odot$, $\chi_\odot$ is the angle between the direction of polarization and the flare-to-disk-center direction.

4 POSSIBLE EXPLANATION AND DISCUSSION

Significant linear polarization has been detected in the Hα line of the major flare of 2002 July 23. The linear polarization can be due to the impact of electron and/or proton beams. As pointed out by Hénoux et al. (2003a), when beam electrons with energies below 200 eV reach the chromosphere, they will lose their directivity and would not produce polarized radiation. While in the chromosphere, protons with energies below 200 keV will presumably dominate over the high energy part in the energy spectrum. Therefore, there are only two possibilities to explain the observed radial polarization in the flare:

1. Low energy protons move predominately in the vertical direction;

2. High energy electrons move rotationally in the horizontal plane. i.e. electrons rotate around the vertical magnetic field lines and bombard the chromosphere.

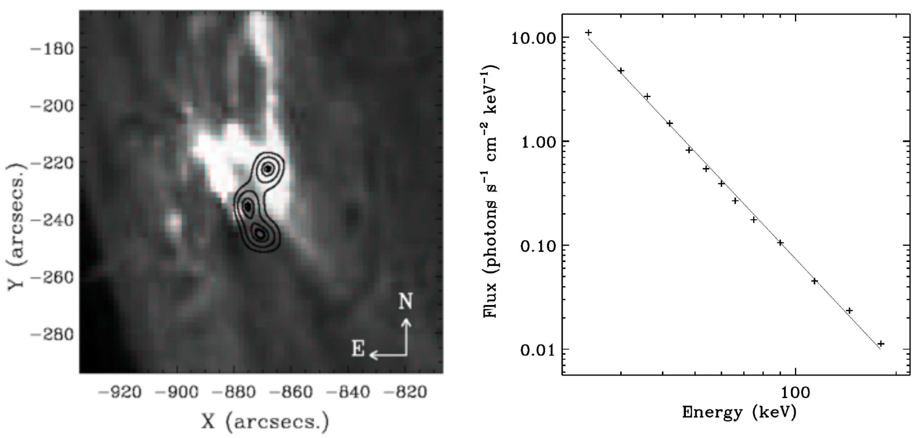

Fig. 7 Contour of RHESSI hard X-ray flux of 24–200 keV superposed on the BBSO Hα image at 00:31 UT (left), and the energy spectrum (right) from which a power index of 3.4 is derived. Note that in this figure North is up, opposite to Fig. 1.

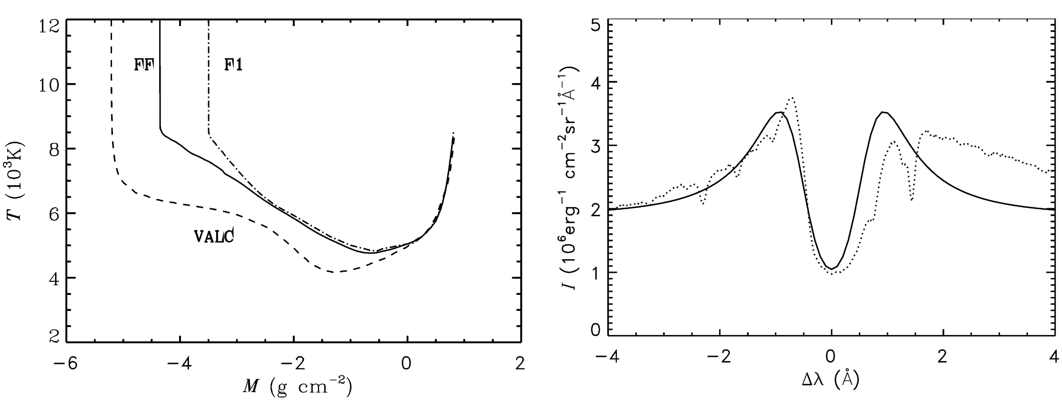

Fig. 8 Temperature distribution of the atmospheric model FF (left), which was used to compute the theoretical Hα line profile (right, the solid line) on the N1 frame. The computation assumed a bombarding electron beam with a total input energy flux $\mathcal{F} = 1 \times 10^{11}$ erg cm^{-2} s^{-1} and a power index $\delta = 4.4$, based on the RHESSI data. The flare model F1 (Machado et al. 1980) and the quiet-Sun model C (Vernazza et al. 1981) are also shown for comparison. Dashed line in the right panel shows the observed Hα line profile.

In fact, RHESSI has indeed observed γ-ray emission in this flare. This implies that there certainly exist high energy protons ($E > 1\,\mathrm{MeV}$), but we do not know if there are low energy protons in the chromosphere. However, our observations show that the Hα line profiles in the early phase of this flare are very broad and have deep central reversal (as seen in Fig. 4). According to the results of some authors (see e.g. Fang et al. 1993), these are the typical characteristics of electron bombardment. Hence we now take up the second possibility and make further calculation.

For computing the Hα line profile with non-thermal excitation and ionization caused by electron beam bombardment, we used the formulas and method given in Fang et al.(1993). From the RHESSI data, we obtained the power index $\gamma = 3.4$. Figure 7 depicts the contour of RHESSI hard X-ray flux of 24–200 keV placed over the BBSO Hα image at 00:31 UT. In the figure, the energy spectrum for the source shown at the left panel is also illustrated at the right panel. Considering the errors in correlating Figs. 7 and 1, we could say that the middle source on the hard X-ray image approximately corresponds to the place where the linear polarization in the Hα line was detected.

From the power law energy distribution of the source, a power index of the electron energy distribution, $\delta = \gamma + 1 = 4.4$, was derived according to the thick target model. By trial and error, a semi-empirical atmospheric model was obtained which can well reproduce the observed Hα line profile as shown in Fig. 8. The figure is meant as an example showing that electron beam bombardment can indeed explain both the Hα line profile and the linear polarization, at least qualitatively.

5 CONCLUSIONS

Our conclusions are as follows:

1. Linear polarization of 3%–10% has been detected in Hα line of the major flare of 2002 July 23, by using spectropolarimetric observations. They are mainly radial on the solar disk and appear just after the peak of the hard X-ray and γ-ray bursts.

2. Change in the direction of polarization in the course of a flare has been discussed in several previous Lyot filter observations (Emslie et al. 2000). However, this is the first time that a change was observed in a limited small region ($\sim 4''$–$5''$) and within a short period of time (~ 10 s). Moreover, the polarization was restricted to some relatively small regions of the flare, particularly where the Hα line has central reversal.

As to the explanation of the linear polarization, electron beam bombardment is a possible candidate. Comparing the results of BBSO and RHESSI, it can be seen that the source of hard X-ray approximately corresponds to the place where linear polarization was detected in in the Hα line. Moreover, our observation shows that the Hα profile during the early phase of this major flare is broad and has strong central reversal, —characteristics typical of electron bombardment. However, protons can also contribute to the polarization: we plan to do a further study on this question.

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