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Integrated Ly-α intensity emission in ribbon flares

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Abstract. We have analyzed two flares observed by TRACE in *Lyα* (on 8th September 1999 and 28th February 1999) in order to deduce their morphology, temporal evolution, radiative outputs and compare these results with data obtained in the X-range (SXT and HXT on *Yohkoh*) and with magnetograms (MDI/SOHO). These observational data and the results obtained by a theoretical study of the intensity of the radiation emitted by hydrogen lines, contribute to construct semi-empirical and theoretical models of the chromospheric emission during flares. Future observations by the planned Extreme Ultraviolet Imager selected for the Solar Orbiter mission -which will have a Lyman alpha channel- and this work, can help in designing observational flare studies.

Key words. Sun: activity – flares – X-rays

1. Introduction

The collisional thick target electron beam heating model for a flare proposes that the chromospheric flare heating and enhanced radiation arises as a result of energy deposition and ionisation by a beam of electrons accelerated in the corona. The electron beam model has proved reasonably successful in the context of both *Lyα* and *Hα* observations (Radziszewski et al. 2007) and we use this as a working hypothesis in interpreting the observations presented here.

We have studied two different flares observed by TRACE at 1216 Å and 1600 Å channels. We corrected the 1216 Å images using the procedure proposed by Handy et al. (1999), to estimate the flare *Lyα* intensity. The 1216 Å channel is strongly contaminated by lines of CIV, so the correction involves taking a linear combination of the intensities in the TRACE 1216 Å and 1600 Å (CIV) channels.

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2. NOAA 8690

In active region NOAA 8690, an M1.4 flare (with peak at 12:13:20 UT) occurred on 1999 September 08. 1216 Å and 1600 Å TRACE images, to study this flare, we used also X-ray data from SXT and HXT onboard *Yohkoh* (Rubio et al. 2009).

Fig. 1 (top panel) shows the overlay of soft X-ray emission on *Lyα* images. The first two images are from the impulsive phase, and the third is from the gradual phase. The bright emission seen in the *Lyα* images is spatially

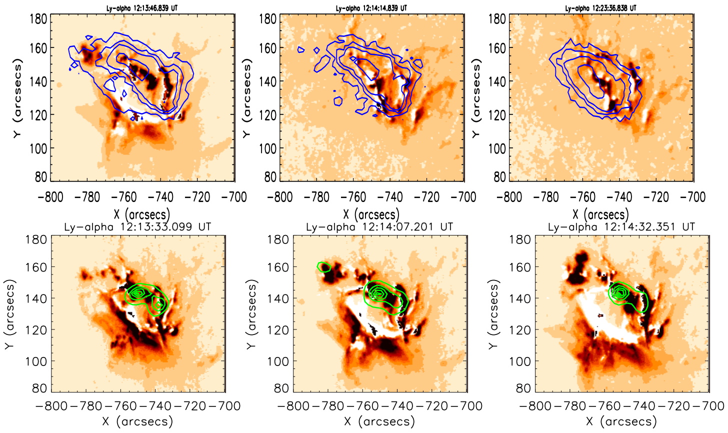

Fig. 1. [top]: Temporal evolution of the Yohkoh/SXT source (blue contours), using the Be filter data, superposed on the nearest *Lyα* images. The contour levels are 1%, 5%, 10% and 50% of the peak counts in each SXT image. [bottom]:Temporal evolution of the 33-93 keV source (green contours), superposed on the nearest *Lyα* images.

well correlated with the strongest emission seen in the SXT images.

Fig. 1 (bottom panel) shows the hard X-ray flare sources overlaid on *Lyα* emission. The hard X-rays sources and the *Lyα* footpoints show a good coincidence.

The hard X-rays light curves from the early impulsive phase and in the gradual phase are shown in Figure 2. Only the earliest part of the impulsive phase was observed before the *Yohkoh* data downlink. The flare was in its gradual phase when observations started again.

Using data acquired during the first minute of the impulsive phase observed by *Yohkoh*/HXT, we calculated the electron beam power under the assumption of a chromospheric collisional thick target. We fitted the photon spectrum using the equation:

$$I(\epsilon) = A\epsilon^{-\gamma} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}, \quad (1)$$

where I is the photon flux at the energy ϵ in keV, γ is the power law index and A is a normalisation constant.

The results indicate that the spectrum is well fitted by a power law with index 3.40, which indicates a very hard spectrum, therefore we can conclude that the hard X-ray emission above 14 keV was produced by nonthermal electrons.

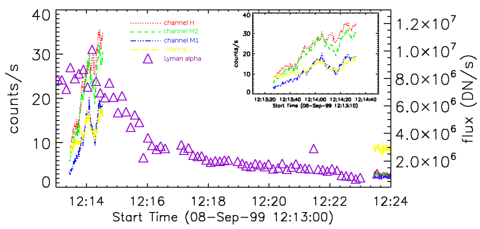

Fig. 2. Time profile of corrected TRACE *Lyα* flux shown as purple triangles, and hard X-Ray counts/subcollimator/second taken with *Yohkoh*/HXT. The four different channels are 14-23 keV (L), 23-33 keV (M1), 33-53 keV (M2) and 53-93 keV (H). The small box shows the HXT time profiles at the beginning of the flare at higher time resolution.

Moreover, we deduced the instantaneous electron energy flux at injection, above some ‘cut-off’ energy E_c, assuming that the power-law part of the spectrum is generated by electron-proton bremsstrahlung in a collisional thick target process. Assuming the Bethe-Heitler cross section, the following equation can be used (Fletcher et al. 2007):

Table 1. Parameters derived from *Yohkoh*/HXT data. Power law index γ (3.399 ± 0.008) and the normalization constant A ($[2.43 \pm 0.08] \times 10^5$) are from the fit to a single power law.

E_C	P
$15*10^{27}$	8.61 ± 0.28
$20*10^{27}$	4.31 ± 0.14
$25*10^{27}$	2.53 ± 0.08

$$P(E \geq E_c) = 5.3 \times 10^{24} \gamma^2 (\gamma - 1) * B\Big(\gamma - \frac{1}{2}, \frac{3}{2}\Big) A E_c^{1-\gamma},$$

where B is the beta function and A is the normalization constant of the photon spectrum $I(\epsilon)$. We used three values of E_c and calculated the instantaneous beam power carried by electrons above this energy. In Table 1, we present the parameters derived from the single power law fit. These values are consistent for a small M-class flare, and are also adequate to power the $Ly\alpha$ losses.

3. NOAA 8471

The flare occurred on 1999 February 28 in active region NOAA 8471 was catalogued as a M6.6 class flare, with a maximum at 16:42:06 UT. We used 1216, 1600 and 171 Å TRACE images and some magnetograms acquired by MDI, in order to study the event and the evolution of the magnetic field configuration.

The 171 Å TRACE image (see Fig. 3 middle) shows the configuration of the flare loops at the impulsive phase. In the early stage of the impulsive flare phase (at 16:33 UT), TRACE 1216 Å and 1600 Å images show a plasma eruption blowing up from the flare site, without any clear flare ribbon (see Fig. 3 left).

Using the potential field extrapolation method introduced by Alissandrakis (1981), we have reconstructed the 3D magnetic field above the photosphere, using the MDI magnetogram acquired before the flare (at 13:10:02 UT) (See Fig. 3 right). The comparison between the 171 Å image and the potential field extrapolation shows a good agreement.

Table 2. Observed $Ly\alpha$ intensities for the two flare studied. The values are given in $ergs^{-1}cm^{-2}sr^{-1}$.

Flare	$Ly\alpha$ Intensity
08/09/1999 (M1.4)	$2.68 * 10^7$
28/02/1999 (M6.6)	$4.21 * 10^6$

Table 3. Calculated $Ly\alpha$ intensities for 6 different flare models. The values of the intensity are given in 10^6 $ergs^{-1}cm^{-2}sr^{-1}$.

Model	$\mu = 0.2$	$\mu = 0.6$	$\mu = 1.0$
F1	3.01	3.05	3.11
F2	6.14	6.29	6.50
Model 1	5.90	6.10	6.27
Model 2	8.31	8.53	8.80
Model 3	3.76	3.90	3.98
Model 4	5.89	5.95	6.09

4. $Ly\alpha$ Intensity

In Table 2 we report the $Ly\alpha$ intensity estimated for both flares at the footpoints (for details see Rubio et al. (2009)).

We computed the electron and hydrogen level population and hydrogen line profiles in order to describe the variation of hydrogen lines during flares.

We used two temperature-height distribution flare models given by Machado et al. (1980): F1 is for faint flares and F2 for brighter flares. Some different models between F1 and F2 have been constructed (like a linear combination between F1 and F2) to study how the intensity of the $Ly\alpha$ line emission might change with the variation of the temperature and the microturbulent velocity at different layers. We calculated the value of the integrated intensity under the profile of the $Ly\alpha$ line for different values of $\mu = \cos\theta$, where θ is the angle between the normal and the line of sight (see Table 3).

Comparing these values with the values inferred from the $Ly\alpha$ images, we can deduce that the measured $Ly\alpha$ intensity at the flare

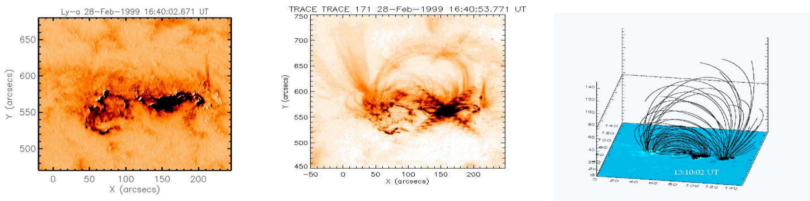

Fig. 3. [Left]: Temporal evolution of the flare in $Ly\alpha$ at the maximum of the impulsive-phase of the flare. [Middle]: Image of the flare at 171 Å. [Right]: Potential magnetic field extrapolation of the active region NOAA 8471 some hours before the flare, at 13:10:02 UT.

Table 4. Values obtained using different models of temperature and changing the microturbulent velocity. The values of the intensity are given in $10^6\ ergs^{-1}cm^{-2}sr^{-1}$.

Mod.T	Mod.υ	μ = 0.2	μ = 0.6	μ = 1.0
Mod.1	$v1$	5.90	6.09	6.27
	$v2$	5.35	5.67	5.86
	$v3$	6.10	6.17	6.30
Mod.2	$v1$	8.31	8.52	8.78
	$v2$	7.67	8.08	8.38
	$v3$	8.65	8.67	8.85
Mod.3	$v1$	3.76	3.90	3.98
	$v2$	3.37	3.54	3.64
	$v3$	3.85	3.95	4.00

footpoints in NOAA 8690 is higher than that inferred theoretically.

Moreover, we have constructed three other models, as a linear combination between the two microturbulent velocity models for faint and bright flares.

Table 4 shows the integrated $Ly\alpha$ intensity at different values of μ, using the different models of microturbulent velocity, υ. The broadness of the $Ly\alpha$ line could be a possible explanation of having small effect on the intensity caused by the change of the turbulent velocity.

5. Conclusions

In active region NOAA8690, the majority of the $Ly\alpha$ emission originates from the flare footpoints, which are compact and co-spatial with the HXR sources, displaying an impulsive phase. The corrected $Ly\alpha$ peak is at, approximately, the same time as the hard X-ray (within a minute). We have calculated the power radiated in the $Ly\alpha$ footpoints, and shown that, for the flare occurred in NOAA 8690, this can be provided by the electrons which produce the observed hard X-ray radiation, under the assumption of a collisional thick target chromosphere.

The results we obtained, fitting the spectrum to a power law with index 3.40, indicates a very hard spectrum, therefore we concluded that the hard X-ray emission above 14 keV was produced by nonthermal electrons.

In the event occurred in active region NOAA 8690, the $Ly\alpha$ emission measured at the footpoints is higher than that obtained theoretically.

Estimated $Ly\alpha$ count rates are high from flares such as these, which should enable high cadence imaging for similar or smaller events with instruments such as the EUI on Solar Orbiter, or the LYOT telescope on SMESE.

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