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Analysis of 3B/X2 Class Flare on November 24, 2000 and Associated Phenomena

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In this paper we present the analysis of a dynamic 3B/X2 solar flare from superactive region NOAA 9236 and its associated phenomena. The Hα observations of this flare have been carried out with Solar Tower Telescope at Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India. The flare was also observed by various space- and ground-based instruments like SOHO, TRACE, HXRS, Nobeyama Radio Observatory, etc. The flare shows impulsive nature in different wavelengths, along-with long duration events (LDE) like phenomena viz. associated with type II radio bursts, strong halo coronal mass ejection (CME), proton flare, which are generally associated with LDE. We examined the energetics of CME associated with this flare using SOHO/LASCO data. We found that the potential and kinetic energy increases at the expense of magnetic energy, as the CME moves. This demonstrates that the flux ropes are magnetically driven.

1. Introduction

During the maximum phase of the current solar cycle 23, superactive region NOAA 9236 produced an outstanding series of recurrent major flares and large eruptive events during the period of November 24-26, 2000. The series of homologous flares included five X-class flares and one M3.5 class flare associated with halo coronal mass ejections (CMEs), strong radio bursts and solar particle events [1-6]. Nitta and Hudson [7] outlined the general characteristics of these events, studying mainly the small-scale local activity within the limit of the active region. They noted that the major flares were not long duration events (LDEs) [8] in terms of soft X-ray light curves and morphologies.

The active region undergoing a dynamic restructuring due to continual flux emergence in the form of emerging flux regions (EFRs) [7] and the main magnetic changes are flux emergence in the form of moving magnetic features (MMFs) [5].

The active region produced three X-class flares on November 24, 2000. Here we present multi-wavelength analysis of 3B/X2 flare, which was the first major flare of the series, occurred on 24 November 2000 in NOAA 9236 initiated from the big leading sunspot periphery. The morphology, energetics and dynamics of this flare and associated CME indicate that this flare is impulsive in nature and associated with LDE like phenomena, which is a rare phenomenon.

2. Observations and data reduction

The Hα observations were carried out at the Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India, using 15 cm Coude telescope and Lyot filter centered at Hα line. The Hα image was enlarged by a factor of two using Barlow lens. The resolution of the Hα image is 0.65"/pixel. In this study we also used the SOHO, TRACE and HXRS data. This data was taken from the archive.

The data reduction and analysis have been done using the softwares like IRAF and Solarsoft.

3. Results

3.1. Hα and other emissions

The active region NOAA 9236 was a large, fast growing βγ region consisting of a large spot of positive (leading) and smaller negative (trailing) polarity spots with the magnetic field of average magnetic intensity, but high shear at the flare location. The vector magnetogram taken before the flare onset from Mitaka, Japan, shows high shear ~ 80 – 90^0 near the flare location.

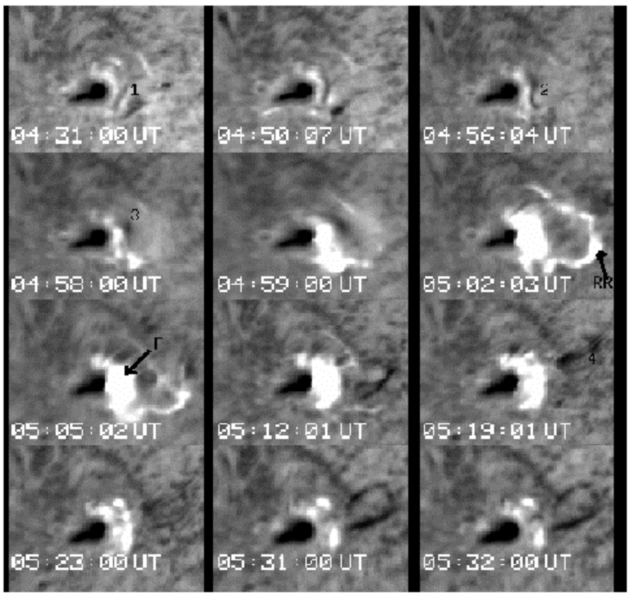

Fig. 1. Selected Hα images (282"x225") of 24 November 2000 flare. In the figure F denotes the core and RR denotes the remote ribbon.

Fig.1 shows the evolution of 3B/X2 solar flare and eruption of filament in Hα on 24 November 2000 on the western side of the leading sunspot along the neutral line. The location 1 at 04:31:00 UT indicates the filament arches and 2 at 04:56:04 UT indicates that the filament arches changed into sigmoid like dark filament. There was a break (3) in the middle of the filament at 04:58:00 UT and then the dynamic eruption of twisted filament started. The disappearance of this twisted filament was followed by 3B/X2 multi-ribbon eruptive flare. The flare has basically three ribbons, two are located at the area F, near the neutral line and the third one is a remote ribbon represented by 'RR' in Fig.1 which is connected to the main two ribbons. The two ribbons are also clearly visible in UV at 1600 Å observed by TRACE (c.f. Fig. 3). These ribbons are separated from each other as the flare progress, owing to successive magnetic reconnection. The average separation speed of flare ribbons is ~ 50 km· sec^{-1}.

The remote ribbon is much more fainter than the main flare ribbons and propagates outwards from the sunspots and main flare site, at a maximum speed of ~ 80 km· sec^{-1}. The remote ribbon may be due to two possible mechanisms: (1) the eruptive filament channel creates a shock front and the projection of this shock is seen in the chromosphere in the form of remote ribbon; (2) the erupting filament/fluxrope interacts with outlying coronal loops. Then as a result of reconnection, the remote ribbon formed by the particle traveling along the field lines gets precipitated in the chromosphere. The remote ribbon retracted after reaching the maximum separation. This retraction may be due to the falling back of the part of eruptive flux rope.

The flare ribbons comprise of several Hα kernels that evolve differently. To analyze the evolution of spatially resolved flare emission we selected six Hα kernels located at area F. The selected six kernels are presented by K1, K2, K3, K4, K5 and K6 in Fig. 2 (left).

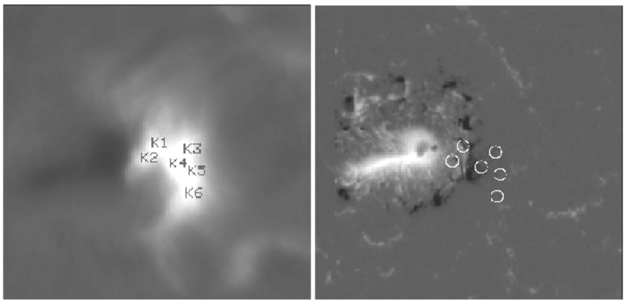

Fig. 2. Selected Hα (05:02:03 UT) flare kernels (left) and their position in photospheric magnetogram (right, 04:48:02 UT). The FOV of images is 200"x 200'.

To see the magnetic topology of these kernels, in Fig. 2 (right) we overplot these kernels into the photospheric magnetic field. We measured the magnetic field strength of each Hα kernel and found that all these kernels to have weak magnetic field strength and located near the magnetic neutral line. The two-ribbon structure, also seen in TRACE 1600 Å image, is connected with bright loops (c.f. Fig. 3). The remote ribbon is faint as compared to main ribbons in the southwest direction. The Hα and TRACE 1600 Å images show similar structure of the flare. The morphology of the flare, for example, the location and the evolution of the ribbons, are quiet similar.

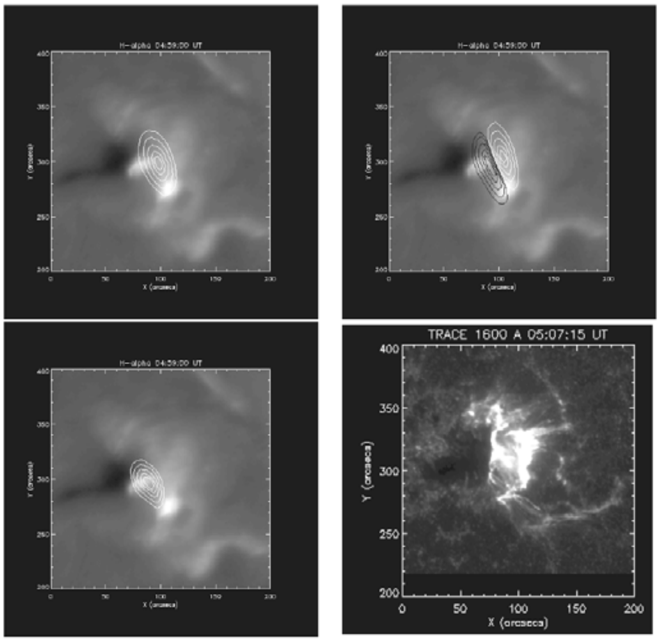

Fig.3. Hα images overlaid by MW (17 GHz I (top left), V (top right)) and 34 GHz (bottom left) contours (contour levels are 10%, 25%, 50%, 75% and 90% of the peak brightness temperature, which is 2.4 X 10 8 K at 17 GHz and 1.1 X 108 K at 34 GHz) and TRACE (1600 Å) image of the flare.

To investigate the heating effect of the non-thermal electrons on the Hα emission, we construct the radio 17 GHz (I and V) and 34 GHz (only I, because there is no V observation at 34 GHz) images observed by Nobeyama Radio Heliograph (NoRH). The overlaid map of microwave (MW) (17 I, V and 34 GHz I) on Hα images are shown in Fig. 3 during the flare peak. The MW sources at both frequencies (17 and 34 GHz) are elongated in north south direction above the Hα flare ribbons and seems to be located at the loop top. The emissions at 17 and 34 GHz are consistent with each other but the size of 34 GHz source is smaller than the 17 GHz source. The true radio source sizes can be determined by treating the source in each radio map as the convolution of the true source (assumed to be two-dimensional Gaussian in shape) with the Gaussian used for restoring beam in the map. We have estimated the resulting "deconvolved source size" at the time of two MW peaks for this flare. The values are 25"x 15" at 17 GHz, 11" x 9" at 34 GHz during first MW peak and 28" x 17" at 17 GHz, 8" x 9" at 34 GHz for the second MW peaks respectively.

At 04:59:00 UT the 17 GHz source is right as well as left handed circularly polarized, with a structure indicating that the two components are not clearly separated. This suggests that MW source is a bipolar loop, but the sizes are too small to be clearly resolved by the available instrumental resolution of NoRH.

3.2. Temporal evolution

To see the temporal evolution of the Hα kernels (K1, K2, K3, K4, K5 and K6) in Figs. 4 and 5 we plotted the variation of the relative intensity of these flares kernels as a function of time. On the temporal evolution of these

Hα kernels we can say that the kernels K1, K3 and K4 show one type of temporal evolution and resemble with HXR 20.0–44.0 keV energy bands, while kernels K2, K5 and K6 show another type of temporal evolution, resemble with HXR 44.0 - 67.2 keV energy band. The temporal evolution of the flare shows sharp rise suggesting the impulsive nature of the flare.

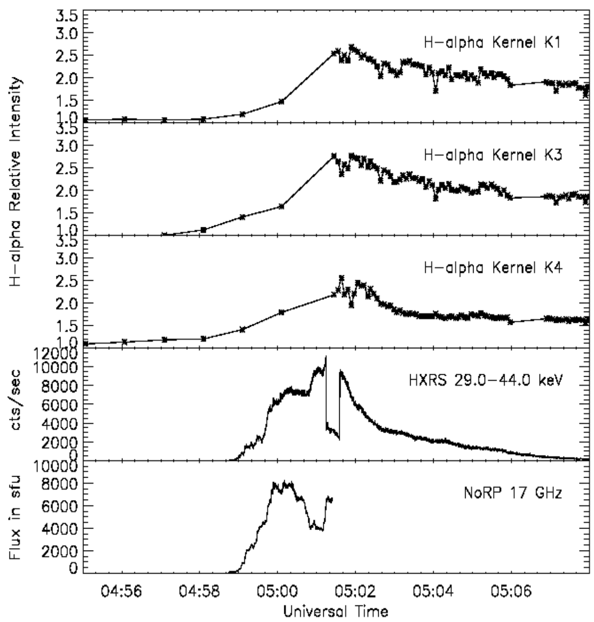

Fig.4. Temporal evolution of flare kernels K1, K3, K4 and HXR (29.0 – 44.0 keV) and NoRP 17 GHz.

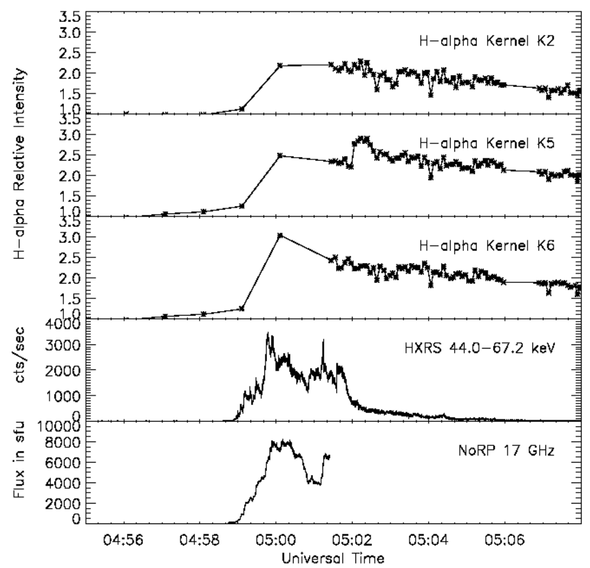

Fig.5. Temporal evolution of flare kernels K2, K5, K6 and HXR (44.0 – 67.2 keV) and NoRP 17 GHz.

To examine the non-thermal electrons, we also used the MW total flux measured with NoRP (17 GHz) and HXR data of HXRS. Figs. 4 and 5 (bottom panel) show the light curves of MW (17 GHz). Light curves of HXR show two main peaks almost at all energy bands. We noticed that as the energy bands increase, the second peaks of HXR emission become more prominent in comparison to the first peak. The profiles also show more spiky nature at higher energy bands. Comparison of MW (17 GHz) and HXR high energy light curves indicates that they are quiet similar. The similarity between these two indicates that they both are originated from the same population of electrons.

We derived the temperature and emission measure of the flare using GOES two-channel diagnostics [9]. The maximum value of temperature and emission measure is 24 MK and $7{\cdot}10^{49}$ cm^{-3}, respectively. Our calculated values of temperature and emission measure are very close to the study by Feldman et al [10].

3.3. LASCO/CME observations and dynamic radio spectra

LASCO/SOHO observed a full halo CME on 24 November 2000, associated with the 3B/X2 solar flare. SOHO/LASCO C2/C3 images of CME appear as a bright front over the northwest limb, and become a full halo extending over 360^0. In LASCO C2/C3 images in the northwest direction twisted flux rope like structure is visible which gets detwisted/stretched during an eruption. The average speed of the CME derived from the height-time plot is about 900 km$\cdot$ sec^{-1}.

Using the LASCO data we measured the mass and energetics of the CME associated with studied flare [11]. The estimated value of the CME mass is $5.5{\cdot}10^{15}$ g and the variation of kinetic, potential, magnetic and total energies are shown in Fig. 6.

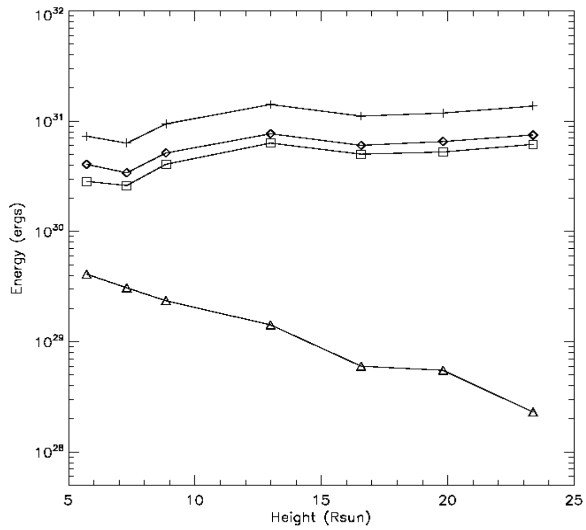

Fig.6. Variation of potential (square), kinetic (diamond), magnetic (triangle) and total (plus) energy of the CME with heliocentric height.

Since large solar flares generate strong shock waves we can expect that both the rapid (impulsive) and prolonged (delayed) acceleration mechanisms are active in such flares. The latter is manifested by shock waves and acceleration of particles in to corona and interplanetary space.

The current flare was associated with different type of radio bursts. The dynamic radio spectra observed by HiRAS shows the presence of a group of fast drifting radio bursts (type III) around 05:00 UT. Strong type II radio bursts (05:02–05:11 UT) with harmonic structure observed in the frequency range 180-30 MHz, with an estimated speed of ~ 1000 km· sec^{-1}. The flare was also associated with an interplanetary type II radio bursts starting from 05:10 UT in the frequency range 14 MHz – 100 KHz, following the coronal type II radio burst.

4. Discussion and conclusions

We studied the 3B/X2 flare on 24 November 2000, which included the various ground and space-borne observations including ARIES (Hα observations), NoRH/NoRP (radio observations), SOHO, TRACE and HXRS.

The studied flare shows three Hα ribbons. Two are merged to each other and located at the location of filament eruption site near the western edge of big leading spot. The third ribbon, which we call the remote ribbon, is away from the main flare site and it is well connected with the main flare ribbons by flux rope at the southern end of the ribbons. This shows the movement along the direction of filament eruption. The speed and direction of the flare ribbon 'RR' agrees with those of erupting filament.

The comparison between the Hα and MW images shows that the MW source (in both 17 and 34 GHz) is elongated and located above the Hα ribbons like a loop with peak close to the loop top. In many cases [12-14] such morphologies have been attributed to optically thick sources: when the emission is optically thick, usually, the MW peak occurs at the loop top because the magnetic field is lowest there and hence the electrons will have higher effective energy. Comparing the sizes of 17 and 34 GHz sources we show that the 34 GHz source, appearing to be smaller, this might be due to two reasons: (1) their true dimensions are smaller than the true dimensions of the 17 GHz source; (2) the restoring beam size decreases with frequency. The latter has been reported by many authors (i.e. [15-17]), which occurs due to the inhomogeneity in both the number density of energetic electrons and the magnetic field strength.

From the comparison of time profiles of different kernels in Hα one can see that the light curves of kernel K1 correlate with kernels K3 and K4 while the light curve of kernel K2 correlates with kernels K5 and K6. From this co-relation of different kernels we can conclude that the Hα kernels are the conjugate footpoints of the Hα flare ribbons with the different magnetic polarity.

The analysis of the CME energetics of flare reveals that the kinetic and potential energy are increasing with the heliocentric height while the magnetic energy is decreasing. As a result of this the total energy (kinetic + potential + magnetic) of CME remains constant. We can explain the increase of kinetic and potential energy at the expense of the magnetic energy. The decrease of magnetic energy is a direct consequence of the expansion of the CME. It implies that the untwisting of the flux rope might be providing the necessary energy to the outward propagation of CME in a steady state situation. The flare studied here was impulsive in nature in almost all wavelengths but was associated with a fast halo CME and type II radio bursts, which otherwise is found to be associated with large eruptive or LDE type solar flares.

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