World Academy of Science, Engineering and Technology
International Journal of Physical and Mathematical Sciences
Vol:11, No:3, 2017

X-Ray Energy Release in the Solar Eruptive Flare from 6th of September 2012

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Open Science Index, Physical and Mathematical Sciences Vol:11, No:3, 2017 publications.waset.org/10006590.pdf

Abstract**—**The M 1.6 class flare occurred on 6th of September 2012. Our observations correspond to the active region NOAA 11560 with the heliographic coordinates N04W71. The event took place between 04:00 UT and 04:45 UT, and was close to the solar limb at the western region. The flare temperature correlates with flux peak, increases for a short period (between 04:08 UT and 04:12 UT), rises impulsively, attains a maximum value of about 17 MK at 04:12 UT and gradually decreases after peak value. Around the peak we observe significant emissions of X-ray sources. Flux profiles of the X-ray emission exhibit a progressively faster raise and decline as the higher energy channels are considered.

Keywords**—**Magnetic reconnection, solar atmosphere, solar flare, X-ray emission

I. INTRODUCTION

DURING solar flares, huge amount of energy is released over short time scales in different forms, such as the electro-magnetic radiation (from radio waves through the visible spectrum to γ rays and X-rays), energetic particles (in the form of protons and electrons), and hot plasma eruptions [1], [2]. The energy is stored in the corona prior to the event in the form of stressed or non-potential magnetic fields.

A flare mostly occurs in a closed magnetic field configuration. The fields containing the prominence erupt, the envelope fields will stretch out and the stretched field lines reclose via magnetic reconnection [3]. Such evolution process of a flare called the standard model of solar flares [4]–[6]. The standard flare model successfully describes several observational features of a large eruptive flare, but the basic question about the triggering of the eruption remains debatable. Here the eruption is initiated by reconnection at the corona, well above the core region of the flare [7], [8]. In this manner, the former is built on the concept of an “internal reconnection” while the latter is suggestive of an “external reconnection” [9], [10].

Observations of solar flares in the soft X-rays (SXRs) clearly indicate an enhancement in the flux before the flare, known as the X-ray precursor phase. There is evidence of active pre-flare structures in SXRs cospatial with the flare [11]–[13]. But we should not ignore the fact that significant pre-flare activities may be present even before the X-ray precursor phase in other, longer wavelength observations such as ultraviolet/extreme ultraviolet (UV/EUV) [14].

In the Earth’s ionosphere, as a result of flare X-ray emission, total electron content (TEC) was increased. This perturbation was recorded by Tashkent GPS Station. The sensitivity of the ionosphere to the external influence represents substantial interest because radio communication and navigation depend from the state of the ionosphere [15]. The X-ray variability periods are found great importance and significance in life formation and its evolution on Earth, and therefore, X-ray emission may play a key role in big astro-biological processes [16].

In Section II, we present observational data and technique analysis. Section III is about the flare’s temporal evolution. Section IV shows X-ray spectroscopy of the flare. In Section V we integrate and discuss the observations presented in the previous sections. The conclusions of the present study are summarized in Section V.

II. OBSERVATIONAL DATA AND TECHNIQUE ANALYSIS

For analyzing X-ray light curves and images we use the data sets taken by satellites such as Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and Geostationary Operational Environmental Satellite (GOES). The present X-ray measurements compared with the magnetograms and UV/EUV observations taken by Solar Dynamics Observatory (SDO) [14].

RHESSI, or more rarely Explorer 81 or originally High Energy Solar Spectroscopic Imager or HESSI, is the sixth mission in the line of NASA Small Explorer missions (also known as SMEX). Launched on 5th February 2002, its primary mission is to explore the basic physics of particle acceleration and explosive energy release in solar flares. RHESSI provides spatial resolution of 2 arcseconds at X-ray energies from ~4 keV to ~100 keV.

The GOES supports weather forecasting, severe storm tracking, and meteorology research. GOES spacecraft provide a platform for the Solar X-Ray Imager (SXI). The SXI provides continuous monitoring of the X-ray Sun.

For our analyzing of the data we used some programs in IDL and SSW. IDL is an acronym for Interactive Data Language and SSW is an acronym for Solar Soft Ware. IDL is a computer software system that is produced and sold by Research Systems Inc. of Boulder, Colorado. Solar Soft Ware is a collaborative software development system created at Lockheed-Martin to support solar data analysis and spacecraft operation activities [17].

The RHESSI images have been reconstructed with the CLEAN algorithm with the natural weighing scheme in

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different energy bands, namely, 6-12, 12-25, 25-50, and 50-100 keV [18].

III. EVENT OVERVIEW AND TEMPORAL EVOLUTION

The observations presented here correspond to the active region with the heliographic coordinates N04W71.

The flare was accompanied by a very poor CME (Coronal Mass Ejections) and was detected by the Large Angle and Spectrometric Coronagraph Experiment (LASCO). The coronagraph images (Fig. 2) indicate this CME which had linear speed of 214.5 km/s.

Fig. 3 shows the GOES SXR light curves obtained in two different channels at 1.0-8.0 Å and 0.5-4.0 Å. The wavelength band 1.0-8.0 Å corresponds to energy range of 12.5-1.5 keV while 0.5-4.0 Å band corresponds to energy range of 24.0-3.0 keV. It is interesting to note that there is a very gradual decrease of SXR flux after the peak at 04:12 UT. This feature of the SXR profile is more noticeable in 1.0-8.0 Å light curve. From the GOES flux data, it is recorded as M 1.6 class SXR flare based on the peak intensity of emission. The X-ray flux profiles exhibit a progressively faster decline as the higher energy channels are considered.

According to the GOES reports, the event took place between 04:00 UT and 04:45 UT, with maximum emission at 04:12 UT. It is evident that there is a fast rise during the initial phase of the flare. In Fig. 3, we provide the GOES light curves in 0.5–4 and 1–8 Å wavelength bands.

The RHESSI X-ray light curves are obtained as seen in the Fig. 3. Similar to the GOES profiles, flare emission started at ~04:08 UT in both 6-12 keV and 12-25 keV energy bands. In the 25-50 keV band, we can distinguish two peaks (at ~04:11 UT and ~04:12 UT). In the higher band (50-100 keV) we cannot observe any change in the flux [19]. The time difference, between the peaks of hard X-ray (HXR) flux and SXR flux (~2 minutes) is also noteworthy. For the aim to understand evolution process of the X-ray emission, we have analyzed light curves and images of the flare in three energy bands (see Section IV).

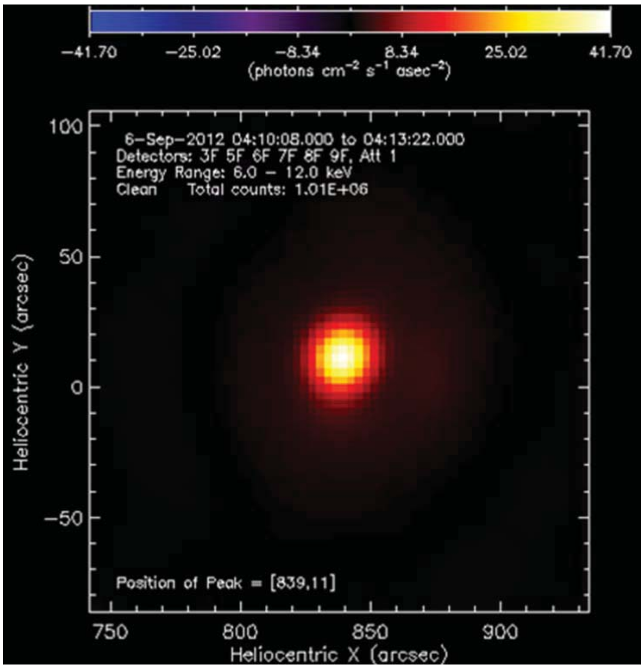

Fig. 1 Reconstructed 6-12 keV energy band RHESSI image

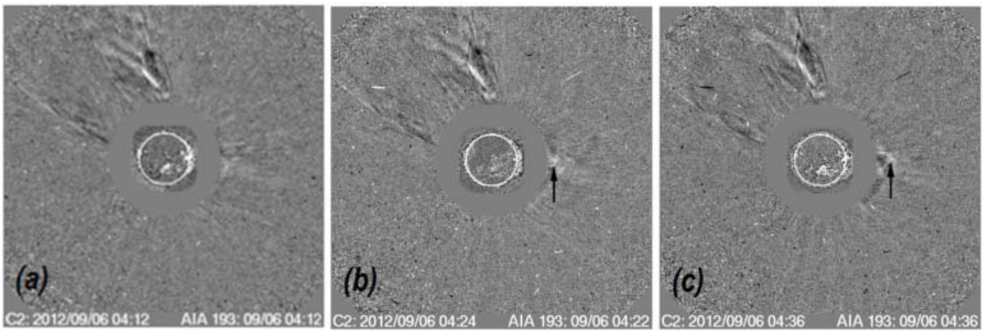

Fig. 2 Image (a) shows solar corona at the peak intensity of the flare. Arrows (b) & (c) mark eruption from the active region. The CME does not appear very prominent in the coronagraph images

IV. RHESSI X-RAY SPECTROSCOPY

RHESSI X-ray imaging and spectroscopic analysis (Fig. 4) was performed to understand the thermal and non-thermal characteristics of the flare emission. The temperature of the flare increases for a short period (between 04:08 UT and 04:12 UT), gradually decreases after peak value and does not increase in the later stages (Fig. 5). Around the peak we observe significant emissions of RHESSI X-ray sources.

The HXR emissions from the flaring loops are traditionally viewed in terms of the thick-target bremsstrahlung process [20] in which the X-ray production at the loop system takes place when high-energy electrons, accelerated in the reconnection region, come along the guiding magnetic field lines and penetrate the denser transition region and chromospheric layers [21]. We observe a low-energy X-ray source (below 25 keV), below the erupting, throughout the flare. We therefore interpret that the low-energy X-ray source indicates the region of X-ray emission from the top of the hot loops.

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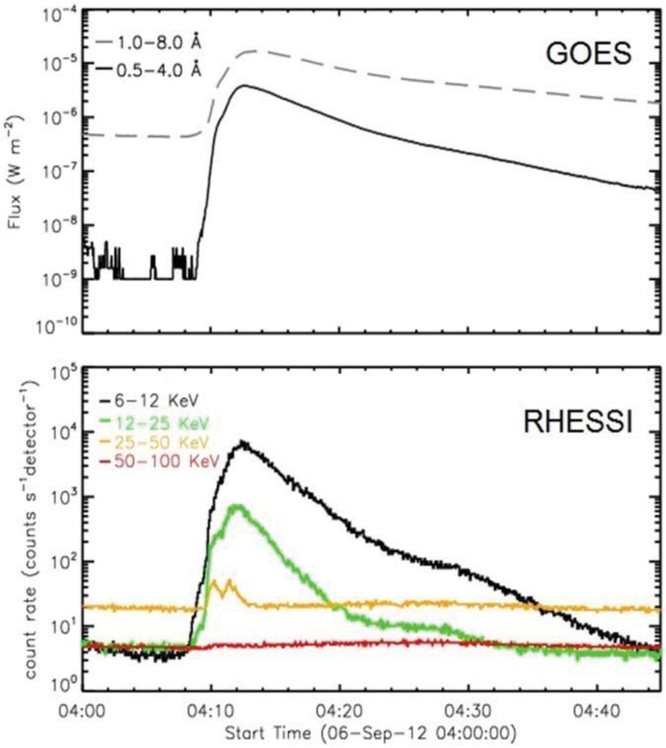

Fig. 3 The GOES time profiles are obtained for 1.0-8.0 Å (12.5-1.5 keV) and 0.5-4.0 Å (24.0-3.0 keV) SXR channels. The RHESSI time profiles are obtained for energy bands of 6-12 keV, 12-25 keV, 25-50 keV, and 50-100 keV

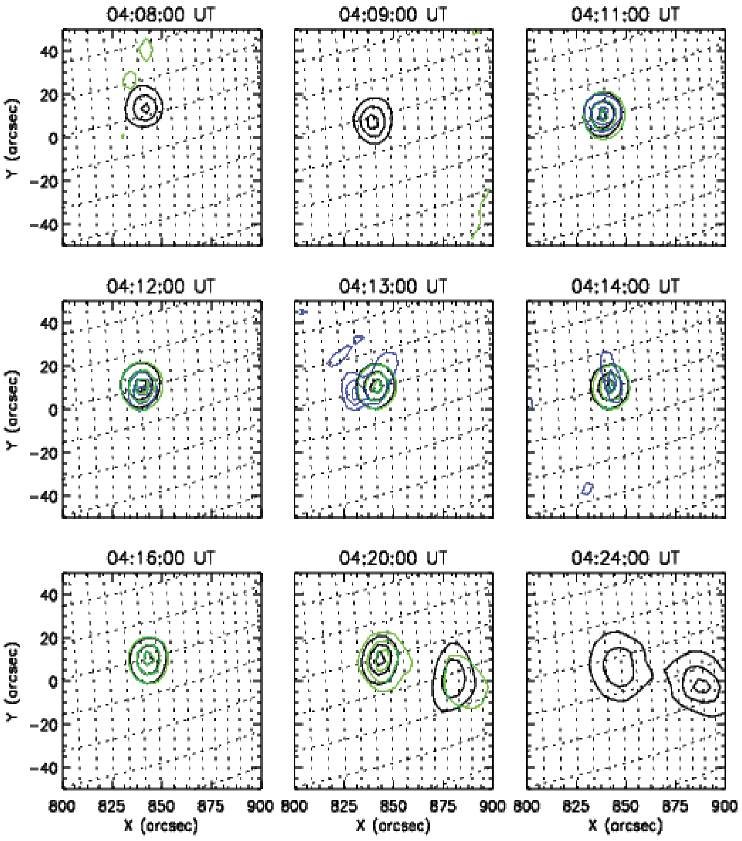

Fig. 4 Images sequence of the temporal evolution of X-ray sources in the 6–12 keV (black), 12–25 keV (green), and 25–50 keV (blue) energy bands

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In Fig. 4, we present images of the RHESSI X-ray sources in 6–12 keV, 12–25 keV, and 25–50 keV energy bands to show the temporal and spatial evolution of X-ray sources. We find that the origin and evolution of the X-ray sources during the precursor phase is very interesting and requires careful examination. We investigate the morphology of the series of images during the flare. The X-ray source at high energy, i.e., 25–50 keV, lies in between 6–12 keV X-ray emission (compare Fig. 4, 04:11 UT). But during evolution of the flaring region, the 25–50 keV emission extends beyond the 6–12 keV band. At 04:14 UT the 25–50 keV emission weakens and decays. The X-ray sources are believed to be produced from different regions of coronal loops (i.e. loop-top, as well as foot-point location).

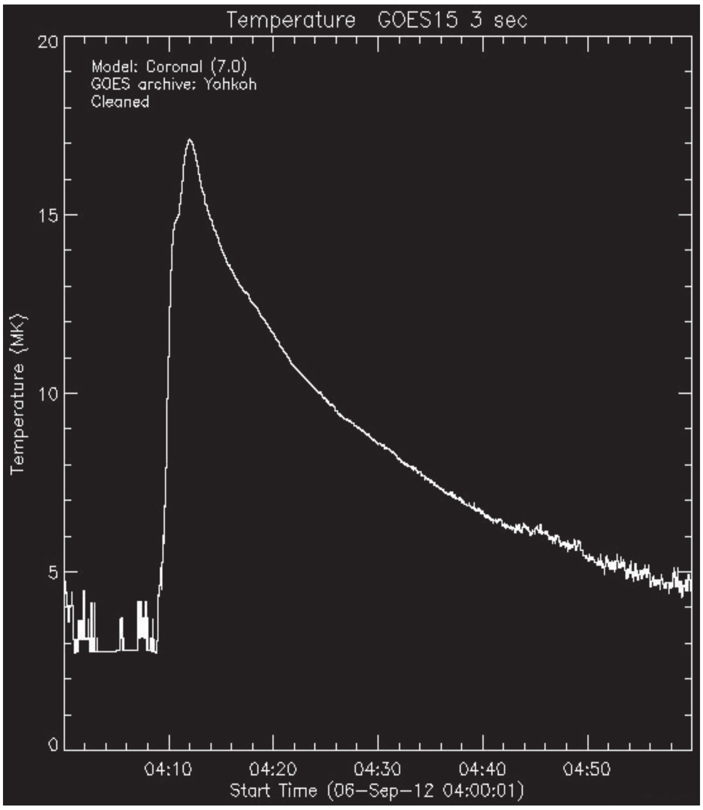

Fig. 5 GOES Temperature profile for the M 1.6 flare on 6 September 2012. The thermal emission peak correlates with flux peak. The maximum value of the temperature is about 17 MK

Very early signatures of the flare are observed in the 6-12 keV energy band (images at 04:08 UT and 04:09 UT) and has a thermal character. But at the time of maximum flux, X-ray sources can be detected in the all energy bands (images at 04:11 UT and 04:12 UT). It is very likely that the HXR sources (25-50 keV) indicate non-thermal emission. The images from 04:11 UT to 04:14 UT indicate emission in the 25-50 keV energy band. Most likely this is due to the particle acceleration process which resulted due to the magnetic reconnection in the corona. In particular, at 04:13 UT and 04:14 UT, the 25-50 keV emission is observed from relatively extended region. After 04:14 UT, impulsive phase of the flare ends as we cannot observe the high-energy X-ray source (25-50 keV). After the impulsive phase we can observe emission only in the 6-12 keV and 12-25 keV bands and emission again has thermal character. From 04:20 UT onward we can see a new X-ray source near to the main source (on the right side). The intensity of the new source increases and by 04:24 UT it becomes more intense compared to the main source. This is probably caused due the fact that the accelerated particles move along different magnetic field lines in the vicinity of flaring region.

The temperature profile of the flare, according to GOES (Fig. 5), confirms our findings. The highest temperature was observed at the maximum as 17 MK. Heating mechanism of the plasma to such high temperatures is still not fully understood [19].

V. RESULTS AND DISCUSSION

The initiation phase represents the initial energy release at distinct locations in a region of highly sheared magnetic fields. It is likely that during this phase a small volume of plasma is heated up at different locations, which is insufficient to produce the detectable level of X-ray emission. The low-energy X-ray emission at this stage originated from discrete volumes of hot plasma and corresponds to emission from ribbons/footpoints and loop-tops.

The plasma temperature rises impulsively and attains a maximum value of ~17 MK at 04:12 UT. The temperature slowly decreases and flare involves a larger volume with the filling of hot plasma in the loop system [22]. The X-ray spectra exhibit a significant non-thermal component during the peak time. Such behavior indicates that each non-thermal emission peak represents a distinct acceleration event of the electrons in the flare [23].

The high-energy HXR source is believed to be closely associated with the site of electron acceleration in the corona [24]–[26]. Coronal HXR emission has been reported in some other RHESSI observations [27]–[29]. However, the physical mechanism for such a strong non-thermal source in the tenuous corona is still not clearly understood. Here it is very interesting to see that the strong non-thermal HXR emission from the source between 04:10 and 04:15 UT. This may occur because of the new magnetic flux continuously fed to the magnetic reconnection site in the corona [3].

VI. CONCLUSION

The flare activities are characterized by energetic X-ray emission. The X-ray emission in 25-50 keV energy band is characterized by high plasma temperatures. The flare is mostly consistent with the standard flare scenario. It is noteworthy that the HXR source became stronger and showed non-thermal emission. The signatures of magnetic reconnection occur in the form of localized instances of energy release. In this manner, one can differentiate pre-eruption reconnection from the post-eruption coronal reconnection that is generally understood in the framework of the standard flare model. Our understanding of the pre-eruption reconnection is still limited because of observational constraints.

So a flare is a magnetic phenomenon. These are regions of strong and complex magnetic fields. The flare studied in this paper provides a scenario of energy release process in HXR and SXR. The HXR profiles are impulsive. This suggests explosive release of huge amount of energy on short time scale. Theoreticians believe that such a violent release of energy can only be explained by the magnetic reconnection process. Our analysis provides evidentiary support for magnetic reconnection and particle acceleration. Due to impulsive energy release in the corona, particles (mostly electrons) are accelerated.

The lower layers of the solar atmosphere, such as the chromosphere and transition region are heated and show emission in longer wavelengths. Sometimes the earliest pre-flare activities can be anticipated with EUV/UV measurements well before the X-ray emission [3].

Observations of solar flares provide us a wealth of knowledge about the basic plasma processes (such as magnetic reconnection) and behavior of magnetized plasma in high temperature environments. Further, the study of solar flares enables us to understand similar process in other stars and astrophysical systems.

ACKNOWLEDGMENTS

We acknowledge RHESSI and GOES for their open data policy. We gratefully acknowledge the support given by the Indian Centre for Space Science and Technology Education in Asia and the Pacific (CSSTEAP, the Centre is affiliated to the United Nations), Physical Research Laboratory (PRL) at Ahmedabad and Udaipur Solar Observatory (USO). This paper contains materials of a pilot project which was made during the 8th CSSTEAP PG Space and Atmospheric Science Course. The author expresses his sense of gratitude to Dr. Bhuwan Joshi, Prof. Hari Om Vats, Mr. Upendra Singh Kushwaha. Also we are grateful to Dr. Bobomurat Ahmedov (Institute of Nuclear Physics of the Uzbek Academy of Sciences) and senior researcher Yusuf Tillaev (Ulugh Beg Astronomical Institute of the Uzbek Academy of Sciences) for directing to CSSTEAP courses.

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