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Observations for the Role of Flux rope Eruption in a Geoeffective Solar Flare

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Abstract

On September 24, 2011 a solar flare of M 7.1 class was released from the Sun. The flare was observed by most of the space and ground based observatories in various wavebands. We have carried out a study of this flare to understand its causes on Sun and impact on earth. The flare was released from NOAA active region AR 11302 at 12:33 UT. Although the region had already produced many M class flares and one X- class flare before this flare, the magnetic configuration was not relaxed and still continued to evolve as seen from HMI observations. From the Solar Dynamics Observatory (SDO) multi-wavelength (131 Å, 171 Å, 304 Å and 1600Å) observations we identified that a rapidly rising flux rope triggered the flare although HMI observations revealed that magnetic configuration did not undergo a much pronounced change. The flare was associated with a halo Coronal Mass Ejection (CME) as recorded by LASCO/SOHO Observations. The flare associated CME was effective in causing an intense geomagnetic storm with minimum Dst index -103 nT. A radio burst of type II was also recorded by the WAVES/WIND. In the present study attempt is made to study the nature of coupling between solar transients and geospace.

Key words: Solar Flare, Magnetic Flux Rope, CME, Geoeffectiveness.

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1. Introduction

Geoeffective Solar transients like Solar flares and Coronal mass ejections (CMEs) originate from the highly complex and twisted magnetic Active Regions on the Sun (Heyvaerts and Hagyard 1991).The intensity of their impact on the space weather and geomagnetic conditions is quite dependent on the location of the active region from which the transients were produced. The mechanism which works behind the process of eruptions or ejection and the features of CME *viz*. angular width, observed velocity also has a vital role to play on the magnitude of effect on geomagnetic conditions.

Electromagnetic emissions from solar flares can be detected practically in all wavelengths from gamma rays to kilometric wavelength of radio waves. Therefore it becomes imperative to take the observation of the Sun in different wavelengths to understand the underlying mechanisms that govern the emission of these wavelengths and at the same time allow us to know how high energy solar transients occur in the solar atmosphere. Observing the Sun in the different wavelengths originated from different layers of it to study the physical mechanisms that operate in these layers, is commonly referred to as Multi-wavelength study.

The flares associated with the CME eruptions are known as “Eruptive Flares”, while the flares without CMEs are known as “Confined Fares”. The emerging magnetic flux, rapid motion, sunspot rotation and interaction of filaments can destabilize the magnetic field, and trigger the solar eruptive phenomena, e.g., flares, CMEs etc. (Min and Chae,2009; Kumar, Manoharan, and Uddin, 2010). Many studies on these phenomena have revealed that the triggering mechanism behind them is related to an unstable magnetic configuration. There are well established theoretical and observational estimations to claim the influence of strong eruptive flares on the triggering of highly geoeffective CMEs (Forbes et.al., 2006). But in many cases, there is a flare association; CMEs can precede the flare (Wagner et.al., 1981).

There is a long lasting question which is centered on the flare and CME relationship, that is, whether the flares are the cause of the CMEs or the CMEs are the cause of the flares. By a statistical analysis of the temporal relationships between flares and CMEs, Harrison (1995) concluded that “The Flare and CME are the signatures of the same magnetic disease, that is, they represent the responses in different parts of the magnetic structure, to a particular activity: they do not drive one another but are closely related”. Recently this question has returned to the attention of solar scientists, partly because space missions like SOHO (Solar and Heliospheric Observatory), TRACE (Transition Region and Coronal Explorer) and recently SDO (Solar Dynamic Observatory) have provided data with better sensitivities, higher temporal and spatial resolutions, to put ideas to further observational tests, and partly because of new studies of physical processes that have benefited from increased computational power. According to Zhang and Low (2005), the question has passed beyond the cause and effect argument. Flares and CMEs are independent MHD processes as Harrison (1995) has pointed out, though they have a great tendency to occur together. So it is more interesting to ask how they occur together and how magnetic reconnection influences the dynamics of CMEs.

Earlier it was believed that the Solar flares are followed by geomagnetic storms after few tens of hours and was suggested that the charged particles from the Sun, rather than electromagnetic radiation, are responsible (Chapmann & Bartels, 1940). Later on Tousey in 1973 discovered CMEs which were often associated with solar flares. The radiations and mass ejections released from the Sun travel through the interplanetary space before impinging on the Earth’s orbit, these CMEs get considerably modified and acquire new characteristics, which may be different from that of the original. These modified forms are termed as Interplanetary CMEs (ICMEs) and these are the ones which interact with Earth’s magnetosphere and are relevant for the evolution of geomagnetic storms. During this interaction the energy carried by the solar wind is transferred to the magnetosphere which then triggers various geophysical processes. In such a case a flare event is said to be Geo-effective.

In our present study we report an observational evidence for the role of erupting flux rope in the triggering of highly geoeffective solar explosion which is associated with CME. Also we have made an attempt to evaluate the mighty impact of this event on the geospace. Not all flares taking place on the Sun are able to produce impact on the Earth. There are a number of criteria which are considered before evaluating the Geo-effectiveness of a solar event. During our study we have not focused on these criteria but only studied in what way it affected the Earth and what was the magnitude of impact.

2. Data sets and Sources

In Active Region NOAA AR11302 at N12E59, an M7.1 GOES class flare occurred on 24 September 2011, starting at 12:33 UT and reaching its peak at 13:17 UT. Figure 1 shows X-ray flux measured by the GOES satellite; the impulsive phase evolution of the flare wasn’t that rapid and after the peak is achieved a much smooth gradual decrease lasting about an hour is observed.

The flare was observed by a number of satellite missions. The observations of Sun in different wavelengths were taken prior to the event, during the event and after the event to study the features of flare in different layers of Sun. The observations of Solar Dynamic Observatory (SDO) Atmospheric Imaging Assembly (AIA) in four different wavelengths 131 Å, 171 Å, 304 Å and 1600 Å were taken for the analysis of M 7.1 solar flare. The AIA provides multiple simultaneous high resolution full-disk images of the corona and transition region up to 0.5 R_s above the solar limb with 1.5-arcsec spatial resolution and 12-second temporal resolution (Lemen, James R et.al 2010). The SDO Helioseismic and Magnetic Imager (HMI) provide full-disk, high-cadence Doppler, intensity, and magnetic images at 1″ resolution (4096×4096-pixel images) of the solar photosphere (Schou, et al. 2011), allowing studies of the sources and evolution of activity within the solar interior. HMI data with highest available resolution is used to study the evolution of magnetic configuration and of the active region.

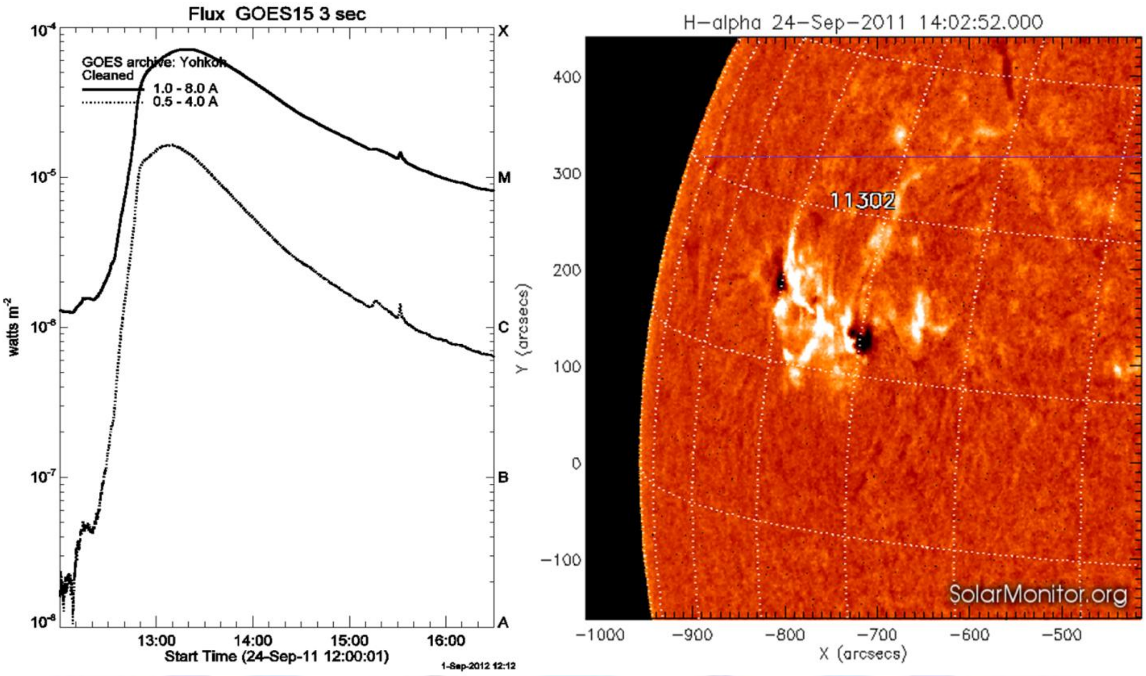

Fig 1: (Left panel) The Soft X-ray flux observed in two channels (0.5-4 Å, 1-8 Å) showing evolution of M7.1 flare Observed by GOES-15. (Right panel) H-alpha image of the NOAA AR 11302 on 24 September 2011 during the M7.1 Flare.

The information of the Coronal Mass Ejection (CME) was taken from the observation made by Large Angle Solar Coronagraph (LASCO) onboard SOHO. Various characteristic features of CME e.g. angular width, speed, onset time etc were taken from the observations of LASCO. The solar wind and Interplanetary Magnetic Field (IMF) data were taken from SWEPAM (D.J McComas et.al.,1998) and MAG instruments (C.W.Smith et.al.,1998) onboard Advanced Composition Explorer (ACE) spacecraft. The IMF has three components namely East-west (By), North-South (Bz) and total intensity B while as the solar wind data contain solar wind density, solar wind speed and solar wind temperature. These data sets are used to describe the conditions in the interplanetary medium and solar wind. The data sets were taken to understand the passage of CME through the interplanetary space. To characterize the effect of CME on the Earth’s magnetosphere we have taken various indices that describe the state of magnetosphere. These data sets were taken from the OMNI data web. We have used Kp, Dst, AE and PCI indices to quantify the magnitude of effect on magnetic environment of Earth. The hourly averaged values of these indices have been utilized for the present study.

3. Observations

3.1 Active Region Evolution

The NOAA Active Region 11302 appeared on solar disc from the North-East limb with a Location coordinate N11E61 on September 23, 2011. The active region was with a beta-gamma magnetic configuration. The sunspot area was reported to be large enough up to 480 millionth of total solar hemisphere. The same day four C-class flares were released from the region. Although the region maintained a similar magnetic configuration (beta-gamma) throughout the next day, the sunspot area widened to 840 millionth of the total solar hemisphere. The number of sun spots was 10, with the time the active region became more complex and released an X class and few M class flares, although the region released a number of flares but its complexity did not relax. On September 24, 2011 the region released an M 7.1 flare associated with a halo CME.

The Helioseismic and Magnetic Imager (HMI) full-disk, high-cadence magnetic images at 1″ resolution (4096×4096-pixel images) of the solar photosphere, were used to study the sources and evolution of activity within the solar interior. Figure 2 shows HMI line of sight magnetograms for September 24, 2011. These images describe the evolution of active region till the M 7.1 flare was released from it. In the images the Bright portions shows the North magnetic polarity while the dark represent the South magnetic polarity. From the figures we see that the active region was highly complex one day before the M 7.1 flare although it has released many C class flares. Even on September 24 the region did not show any signs of relaxation, it continued to evolve even after releasing few M class and an X class flare on the September 24. Both polarities were emerging simultaneously. At the same time the active region was also widening in terms of area. The rotation of the bigger negative (dark) polarity on the eastern part of the active region was clear from the observation, keeping the small white (positive) polarity signs besides it as reference points. This rotational motion of the sunspot, where the flux arcade (observed in 131 Å, 171 Å images) foot points was rooted, might have contributed in building the shear and stress and so led to the high energy storage enough for the big eruption to trigger.

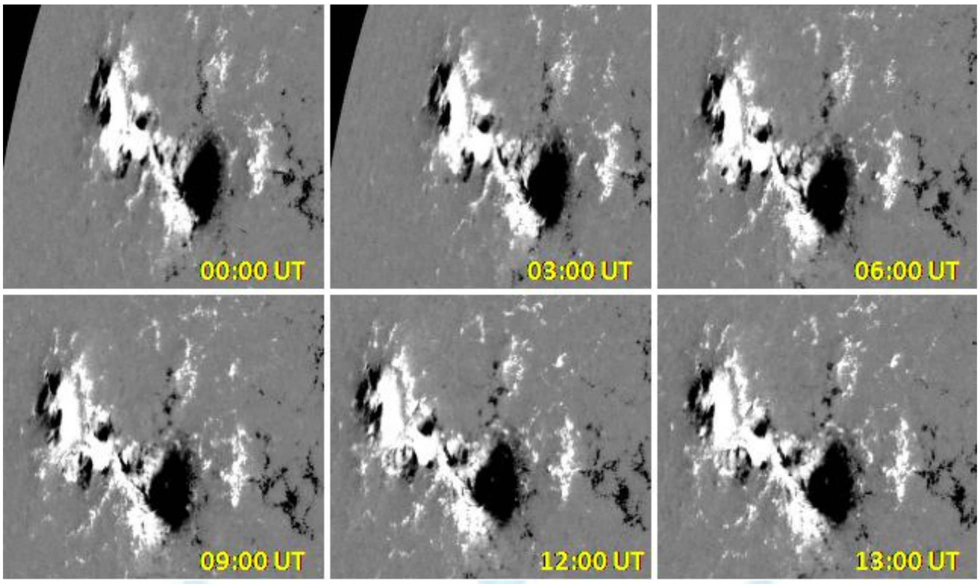

Fig 2: SDO / HMI line-of-sight magnetograms of the NOAA AR 11302 shows the evolution and development of the magnetic configuration of the AR on 24 September 2011 .White regions represents the positive (North) polarity and Black region represents the Negative (South) polarity.

3. 2 SDO Multi-wavelength Observations

3.2.1 AIA 1600 Å

The AIA UV 1600 Å (C $_{\text{IV+cont,}}$ T=4000-10000$_{)}$ observations are taken to observe the transition region and upper photospheric features of the Sun. Figure-3 Shows a typical sequence of the photospheric developments of the Active region 11302 relevant to study the dynamics involved in the M7.1 flare on 24 September 2011. The top panel images were taken prior to the flare. Right from the first image (12:02:41 UT) slight signs of the rising flux rope are observed in this wavelength (indicated by the arrow). The twist and shear developed in the rope with the time is clearly visible in the last image of the upper panel images, which is indicated by the arrow. Just before the flare onset at 12:30 UT, the rope was erupted from the top. The relaxation of this twist and shear is observed in the following images after the Flare onset. As the flare progressed a two ribbon structure became visible, which is represented by R1 and R2 in one of the image, where the flare loops had their photospheric foot points. The two ribbon brightness went on fading as the flare headed in the decay phase and ribbons totally disappeared by the 14:10:41 UT which is the end time as the GOES records.

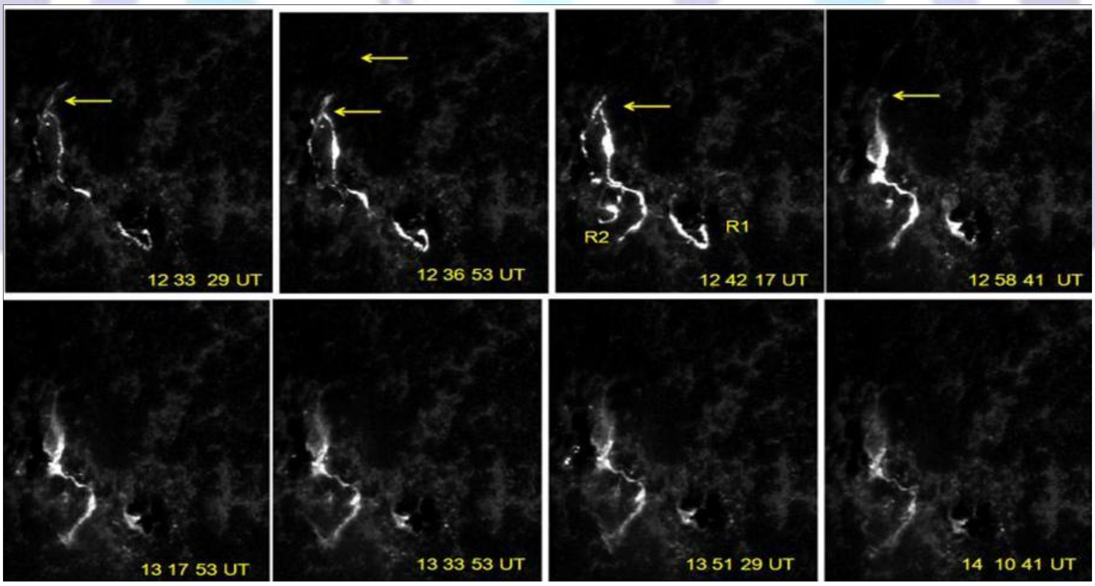

Fig 3: SDO/AIA 1600 Å images, the arrow indicate the activation of Flux rope structure. The two flare ribbons are noted as R1 and R2 in the image.

3.2.2 AIA 304 Å

The observations in 304 Å waveband brings out the upper chromospheric and lower transition region features of the Sun. This wavelength corresponds to the emission from ionized helium (He II) which ori at temperatures around 80,000 K. Figure 4 is a selected but typical sequence of M7.1 flare and the evolution of the flux rope eruption associated with it from the NOAA AR 11302. The images from 11:45 UT, in which the clear presence of the flux rope was observed up to the

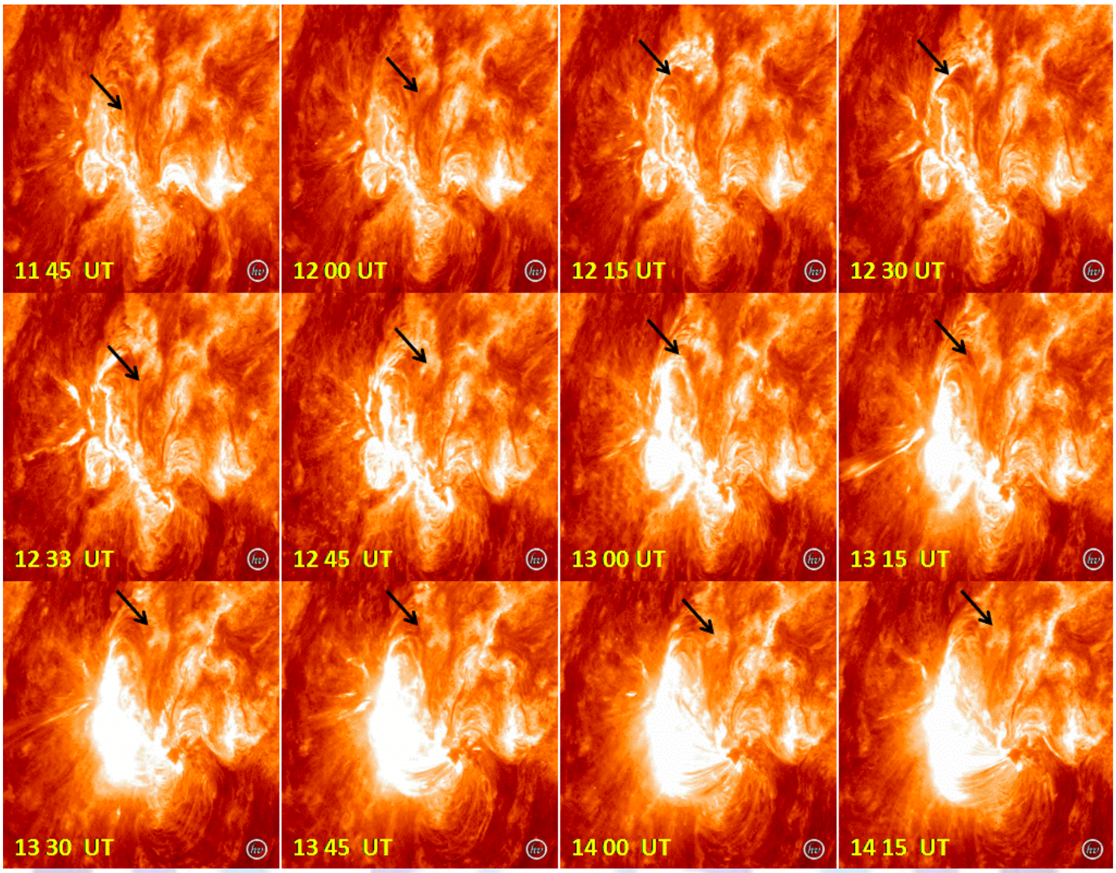

Fig 4: SDO 304 Å (He II) observations the showing the activation of flux rope and triggering of the M7.1 flare in NOAA AR 11302 on 24 September 2011. The arrow points towards the flux rope dynamics.

14:15 UT (GOES end time of the flare), are included in the Figure 4 with a 15 minute temporal cadence (except the 12:33 UT image, GOES start time). These observations shows signs of rising plasma structure maintained at chromospheric temperature as indicated by the arrows. Initially the structure was visible at around 11:45 UT more than 45 minutes prior to the flare onset. Then the plasma associated with the structure started to move upward with considerable pace. Finally, just before the flare onset, recorded by the GOES X-ray, flux rope was erupted at the top of the structure, and it is clearly observable from the 12:30UT image. So this observation leads to a conclusion of the triggering mechanism. As we can see from the LASCO (Figure 7) the mass ejection continued throughout the flare duration.

3.2.3 AIA 171 Å

The obsevations in 171 Å (0.6 MK) are taken to reveal the quiet coronal features and upper transition regional features of the sun. The emision lines contributing to the images in this band are Fe IX and Fe X. The resolution of the images is 4096 X 4096 pixels 1.21” per pixel sampling. The images in 171 Å (Figure. 5) are taken to study the dynamics of the flaring active region and its response in the corona before and during the M7.1 flare. Here the topology of coronal loops, the foot points of which are observed in 1600 Å images (Figure.3) as flare ribbons R1and R2. The loops connect two opposite polarities from positive to negative. Right from 11:45 UT (48 minutes prior to the M7.1 flare) rising plasma structure was observed to exist in the Active region and comaprison with HMI magnetograms shows it to be lying over the Polarity inversion line (PIL). In careful investigation of the AIA movie, this plasma structure was obsreved to rise fastly. At a maximum the rope bursted out (~ 12:30 UT) at the top expelling the the embedded materials out. Just after the explossion took place the flare was triggered at the botom of the structure and GOES X-ray recorded the enhanncement (12:33 UT). As the flare was once triggered , careful investigation of AIA movie showed the plasma flow from the flare site through the sustaining flux rope. The explosion of this flux rope prior to the flare might have caused the highly geoeffective coronal mass ejection which is analyzed later in this paper.

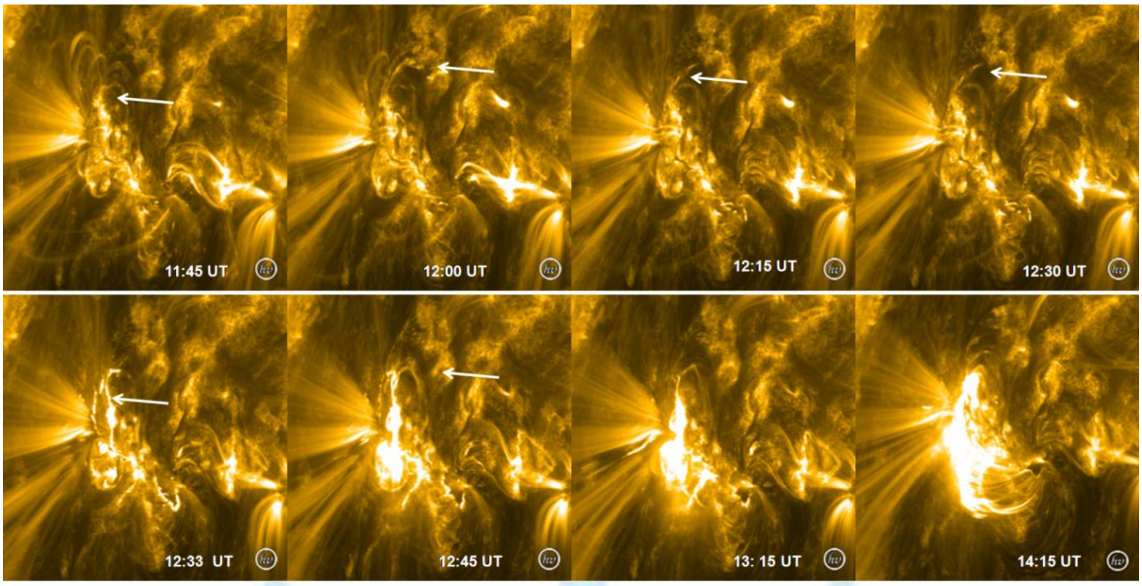

Fig 5: SDO 171 Å (He II) observations showing the activation of flux rope and triggering of the M7.1 flare in NOAA AR 11302 on 24 September 2011. The arrow points towards the flux rope dynamics.

3.2.4 AIA 131 Å

The images taken in wavelength 131 Å, (Fe $_{\text{VIII, XXI}}$ ~10 MK; and cool plasma ~0.4 MK) gives us the information about the transition region and flaring corona of the Sun. These observations also reflect the coronal features, like loop structures, which helps us to trace the magnetic field lines' connecctivity within the active region and between different active regions. The observations taken in this band for the present flare are shown in Figure 6. From the figure, we examine that prior to about one hour of the flare onset a higly twisted flux rope was rising. The flux rope was aligned over the polarity inversioin line (PIL). The high twist and shear developed in the flux rope is clearly visible at (indicated using arrows) 12:30 UT and 12:33UT. The flux rope continued rising with a high velocity till it erupted at 12:25 UT nearly 8 minutes prior to the onset of the M7.1 flare. This erupted structure might have released a huge amount of the solar material which was bounded in it by the time. The dynamics of the flux rope is clearly prominced only in 131 Å images while observation in other wavelengths do not reflect it clearly.The reverse coloured image in the Figure 6 gives us the clear view of the flux rope foot points and its alignment over the polarity inversion line. The rising plasma sturcture was observed simultaneously in allmost all the SDO wavelengths, wich approves the presence of the multi temperature plasma in it.

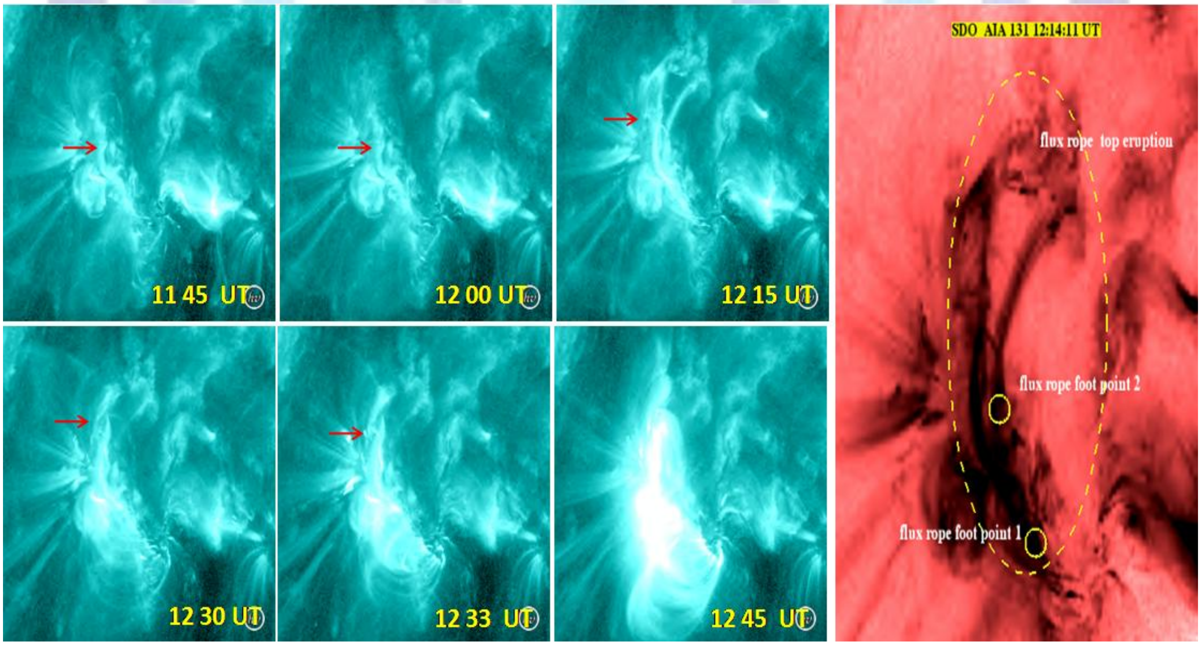

Fig 6: SDO AIA 131 Å ((Fe $_{\text{VIII, XXI}}$,10 MK)) observations showing the activation of flux rope and triggering of the M7.1 flare in NOAA AR 11302 on 24 September 2011. Image size is 170×192 pixels with 0.6 arc sec /pixel resolution. The Arrow points towards the flux rope dynamics. (Right) The 131 Å reversed color image showing the rising flux rope and foot points.

3.3 Interplanetary Observations

3.3.1 Coronal Mass Ejection (CME)

The flare of September 24, 2011 started at 12:33 UT. After 15 minutes of the flare onset LASCO recorded a Coronal Mass Ejection associated with the flare. The CME onset time is taken from the height time profile data found to be 12:48 UT. The evolution of CME with time as recorded by LASCO is presented in Figure7, from C2 coronagraph in gray scale and C3 coronagraph in color. From the figures, we found that the mass ejection took place around the full disk with angular width 360°. Such a CME is referred to as a halo CME and are found to be most effective in causing severe disturbances in the Earth’s magnetosphere. The CME was traveling with a speed of 1710 km/s. The fast moving CME created an interplanetary shock which was detected by the abrupt and sharp increase in the solar wind and Interplanetary Magnetic Field parameters. There was an IP Type II radio burst that lasted all the way to local plasma at WAVES/WIND (Figure.8).

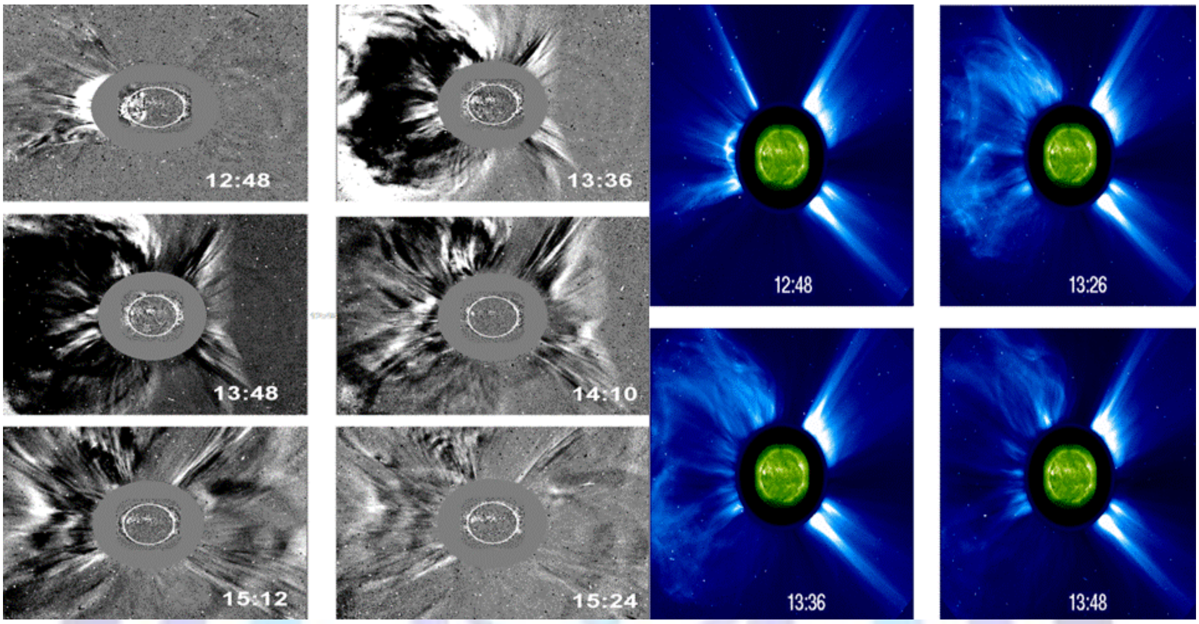

Fig 7: The evolution of halo CME on 24 September 2011 as recorded by the C2 (left) and C3 (right) coronagraph of LASCO.

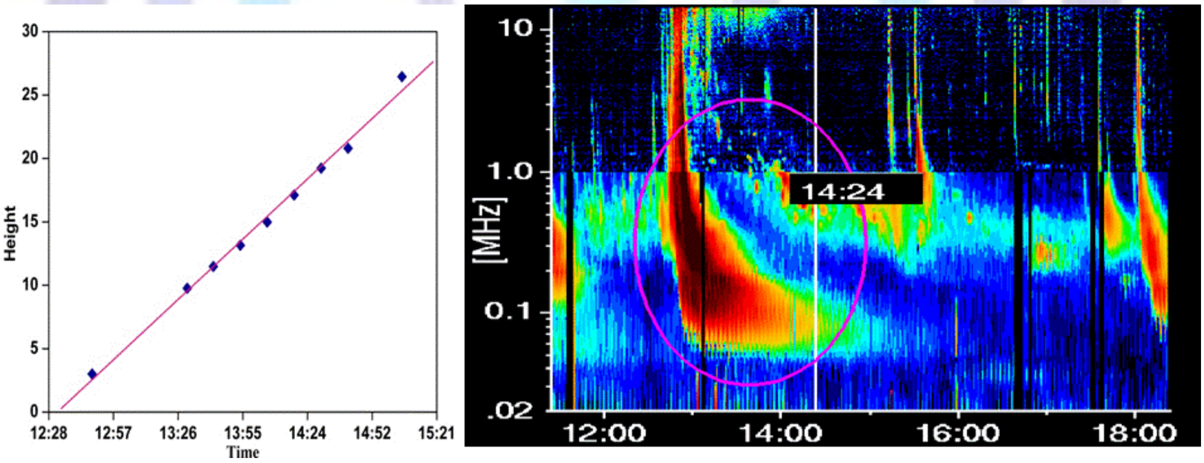

Fig 8: The height-time profile of the CME associated with M7.1 flare from the NOAA AR 11302 at 12:33 UT (height along the Y axis is in Solar Radii Unit). The WIND/WAVES Observed a Type II IP radio burst (right), the time along the X axis is in UT.

3.3. 2 ACE Observations

The conditions of solar wind and Interplanetary Magnetic Field (IMF) were taken from the observations made by ACE spacecraft at LI point. The variation of solar wind parameters and Interplanetary Magnetic Field components are reproduced in the Figure 9. It is evident from the figure that the smooth variation in solar wind parameters and IMF components were replaced by rapid fluctuation during the course of the event. The solar wind velocity increased sharply from 309 km/s to 711km/s indicating an IP shock associated with the CME.

Similarly the values of solar wind density and solar wind temperature increased from 4 particles/cm^3 to 31 particles/cm^3 and 0.06x10^{5}K to 1.0x10^{5}K respectively. The rapid fluctuations were also noticed in the Interplanetary Magnetic Field components. The IMF B_z was northward before the onset of CME. On the impingement of shock the B_z made a southward turning achieving a minimum of -24 nT on September 26, 2011 at 18:31 UT. At the same time the values of IMF B_y and B increased from their normal values to 26 nT and 36 nT respectively.

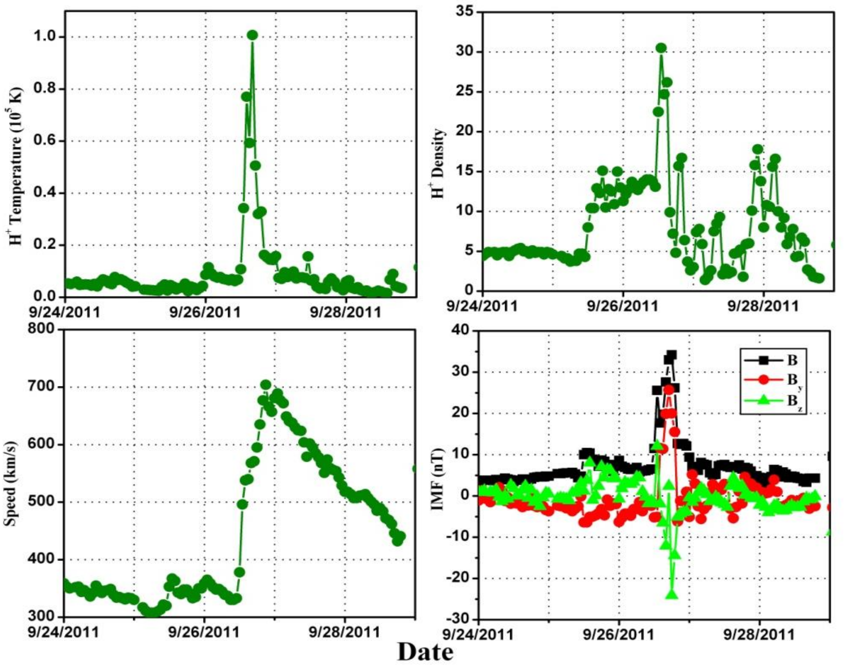

Fig 9: The variation of solar wind parameters and interplanetary magnetic field components after the flare event

3.3.3 Geomagnetic Effects

The energy carried by the CME and solar wind gets deposited into the magnetosphere once CME and shock impinges on the magnetosphere. The energy deposited in the magnetosphere causes severe changes in the geomagnetic field conditions commonly known as geomagnetic storm. The interplanetary causes of geomagnetic storms have been extensively studied (Tsurutani et al.,1992). The Earth-directed solar wind speed and southward component of interplanetary magnetic fields are of atmost importance in enhancing geomagnetic disturbances. The state of magnetosphere during these extreme solar events is described by a number of magnetic activity indices known as geomagnetic indices.

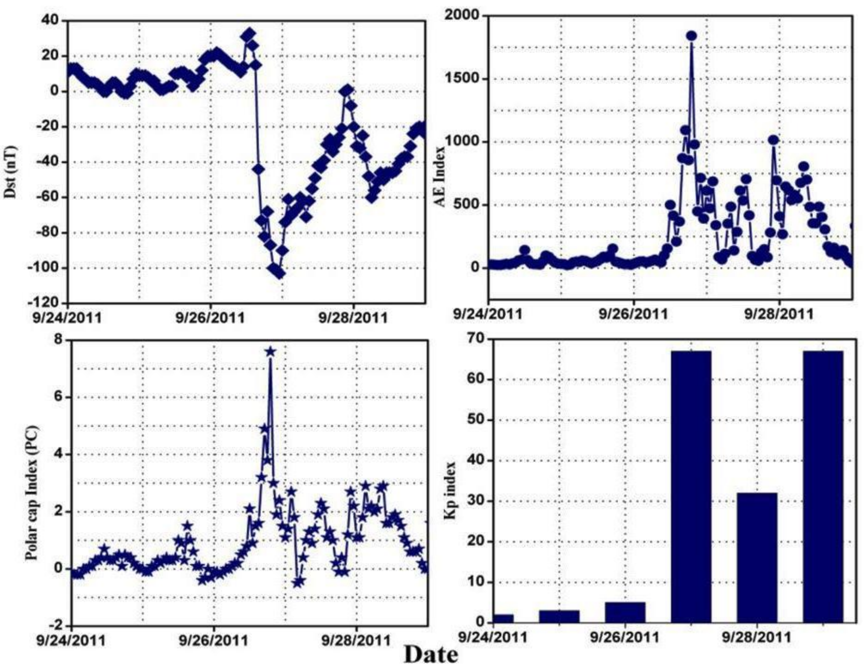

Fig 10: The behavior of various geomagnetic indices showing post flare effect on geomagnetic activity

The geomagnetic signatures of the flare event of September 24, 2011 are reported in Figure 10. From the figure we find that on September 26, 2011, the Dst reached the minimum value of -103 nT indicating an intense geomagnetic storm. The values of Kp also show a very high increase reaching the maximum of 67 indicating a highly disturbed geomagnetic state. Similarly the values of high latitude auroral electrojet (AE) index also increased considerably during the event indicating the onset of various current systems due to increased magnetic field. The polar cap index (PCI) indicating the state that polar cap magnetic field also underwent a sharp change.

4. Discussion and Conclusions

The analysis of M 7.1 flare on September 24, 2011 was carried out in order to understand its initiation mechanism. The analysis showed interesting phenomena that the flare was released from a highly complex active region which evolved very peculiarly and did not relax even after releasing a number of major flares.

The observational results described above in the SDO data analysis section has provided an unambiguous support to the well known CSHKP model of solar flare eruption (references are given). Here the magnetic reconnection occurs at the current sheet which cause the release of the magnetic energy in big amount, and so the flare emission, two-ribbon structures (in some cases multi ribbons also) and post flare loop arcades. Our study provides the strong evidence for the stand that, instability generated on the pre existing flux rope does the trigger. The eruption resulted from catastrophic loss of balance between the upward directed magnetic pressure force and the downward directed magnetic tension force within a sheared core flux system. This triggered the reconnection at the current sheet which likely formed underneath the fast rising flux rope through the upward stretching of the magnetic fields, consequently resulted in the flare. One of the main mechanisms to be involved in such an eruption claimed by Jie Zhang et.al (references there in) is the Torus-Instability (TI), an ideal MHD process responsible for the loss of instability in toroidal current ring. As we observed from the 171Å and 131Å wavelength observations, the fast rising flux rope structure might have caused the formation of current sheet underneath and plasma inflow towards it and so the fast reconnection. Our results suggest that the magnetic flux ropes play a big role in triggering and driving explosive energy release processes in the solar transients and possibly in many other plasma systems in space.

The LASCO observation detected a halo CME associated with the flare. The fast moving CME produced intense increase in the ambient solar wind parameters and Interplanetary Magnetic Field components. When the CME reached the Earth it produced strong changes in the magnetic activity of the planet resulting in an intense geomagnetic storm. The magnetic activity around the Earth was considerably affected and underwent large departures from the normal pattern as evidenced by the magnetic activity indices. Thus we conclude that the flare was a geoeffective one.

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