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Cosmic Ray Intensity and Geomagnetic Activity Variations in Relation to Interplanetary Coronal Mass Ejections during Solar Cycle 24

*** Devendra K. Warwade[1], Mukesh K. Jothe[2],**

Pankaj K. Shrivastava[3], Mahendra Singh[4]

[1]*Department of Physics, C. S. A. Govt. P. G. College Sehore, M.P., 466001, India*

[2]*Department of Physics, Govt .M.G.M. P.G. College Itarsi (M.P.) Pin 461111, India*

[4]*Department of Physics, Govt. P.G. Model Science College Rewa, M.P., India*

[4]*Department of Physics, Govt. P.G. College Alirajpur, M. P., India*

Corresponding Author: * *email: devendrawarwade@gmail.com*,

Abstract:

Interplanetary Coronal Mass Ejections (ICMEs) are the signatures of CMEs associated with interplanetary disturbances, which affect the solar terrestrial environment and produces variations in cosmic ray intensity (CRI) as well as geomagnetic activity. Near earth ICMEs are detected and observed their effects on earth by in situ probes and various space crafts for a long time. We have made an attempt to draw the influences of ICMEs on CRI and geomagnetic indices Dst and Ap index during the period of solar cycle 24. In present study, the total no. of 209 ICMEs are detected and classified into three categories; first of them are magnetic clouds (MC) which have enhanced magnetic field with smooth rotation of large angles, second are complex events which have slow rotation of large angles but lacks of enhanced magnetic field and third are ejecta's (EJ) in which the characteristics of MCs are fully absent. We have investigated the effects of all categories of ICMEs on CRI, Dst and Ap index separately and arrived at the conclusions that all types of ICMEs produces remarkable variations in CRI, Dst and Ap index. Maximum variations are created by MCs. The study reveals that the variations produced by ICMEs are found slightly larger during A>0 epoch of solar magnetic cycle. The speed of ICMEs also have been correlated with CRI, Dst and Ap index, the result of correlation proves the important role of ICMEs speed in CRI variation and geomagnetic activity.

Keywords: Interplanetary coronal mass ejections (ICMEs), Magnetic clouds (MC), Ejecta (EJ), Cosmic ray intensity (CRI), Geomagnetic activity

1. Introduction:

We are familiar from the phenomena of mass ejection from the Sun for a long time. In 1971, using the (OSO-7) seventh orbiting solar observatory, the event of coronal mass ejection (CME) was reported. [Gopalswamy, 2006] investigated that the launching of CME from the Sun bring larger variations in corona which determines the evolution of the magnetic flux of the sun. CMEs produces interplanetary disturbances during their propagation in the heliosphere.

The signatures of CMEs linked with interplanetary disturbances are said to be Interplanetary Coronal Mass Ejections (ICMEs). The CMEs with their leading shock waves are also called interplanetary Coronal Mass Ejections (ICMEs), these are interplanetary counterparts of coronal mass ejections. When CMEs travel in the interplanetary medium, these are observed from the ACE and wind space craft 11. Interplanetary Coronal Mass Ejections (ICMEs) are associated with many characteristics features like speed, low proton and electron temperature. Bidirectional superthermal electron strahls and compositional anomalies are also the features of ICMEs [Cane et.al;2003 and Rechardson et.al;2004]. These anomalies generated geomagnetic storm and produces Forbush decrease in CRI. Many researchers reported that the solar cycle dependent long term/ short term modulation of cosmic rays can be understand by the CMEs

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related magnetic inhomogeneities in the hemisphere [Shrivastava, 2005; Lara et al, 2005]. A subset of ICMEs identified by [Burlaga et.al;1981], which shows a characteristic pattern in which these are accompanied by the increased magnetic field > 10 nT ,with slow and smooth rotation of large angles, such structures are called magnetic clouds[Klein et.al;1982]. These are associated with magnetic flux rope structure. It is seen that the characteristics features of magnetic cloud are not present or partially present in many ICMEs [Burlaga et.al;2001]. When magnetic cloud features are not present, ICMEs are called ejecta (EJ) as defined by [Kim et.al; 2013 and Ibrahim et.al;2019]. Those ICMEs in which characteristics features of magnetic cloud are partially present like field rotation of large angles but lack of enhanced magnetic field, i.e., the events where structures of magnetic cloud cannot be fully defined are referred to as complex events [Ibrahim et.al;2019].

In the present work, we have made an attempt to examine the influences of ICMEs on cosmic ray intensity as well as geomagnetic activity for the period of 2009 to 2020, which covers the whole period of solar cycle 24.Where the ascending phase (2009 -2013) of solar cycle encounters the A<0 epoch of solar magnetic cycle and declining phase (2014 – 2020) of solar cycle encounters the A>0 epoch of solar magnetic cycle. We have also compared the relationship between ICMEs and CRI as well geomagnetic activity during A<0 epoch and A>0 epochs of solar magnetic field.

2. Data and Method of Analysis:

Observations of ICMEs are taken from the catalogue compiled by I. Richardson and H. Cane which contains a list of ICMEs identified by *in situ* probe recently updated up to September 2022. These data is downloaded from website (http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm). Several useful parameters of ICMEs are included in catalogue in which we have noted the starting day of ICMEs, various types of ICMEs as MCs, EJ and Complex events and speed of ICMEs. Daily mean data of Cosmic ray intensity is taken from Moscow neutron monitor during the entire period of study. To observe the influence of ICMEs on geomagnetic activity we have used daily mean data of Dst and Ap index downloaded from website of omniweb. Superposed epoch method of Chree analysis is applied to obtain the results. The CRI, Dst and Ap index are plotted on a large time scale from five days before and ten days after the onset of ICMEs.

3. Results and Discussion:

Earlier it was thought that the cosmic ray modulation is caused by solar flares and solar wind (Rao, 1972; Shrivastava and Shukla, 1994). After the investigation of CMEs in 1971, many researchers have reported the role of CMEs and ICMEs in the cosmic ray modulation processes in long-term/short-term basis (Lara et al, 2005; Shrivastava, 2007, Jothe et.al;2010). Our study aims to verify the role of near earth ICMEs in cosmic ray modulation on short term basis.

Total 209 events of ICMEs are detected and analyzed during the study period in which 89 ICMEs events are associated with the characteristics of magnetic clouds (MC). No. of ICMEs with complex event (CE) character are occurred 79, while the remaining ICMEs say ejecta (EJ) are observed 41 in numbers.

Figure-1 is a plot to represent yearly occurrence of total no. of ICMEs by histograms during the entire period of study. We have also plotted smoothed yearly mean value of sun spot number. Sun spot number is known as a reliable solar activity parameter for a long time. Figure depicts that the variation profile of occurrence of ICMEs follows the pattern of variation profile of sun spot number. Occurrence of ICMEs is large during solar maximum therefore ICMEs can be used as a reliable solar activity parameter. Figure-2 is a pie diagram which represents the % contribution of various subsets of ICMEs events. It is clear from figure that the occurrence rate of those ICMEs events is high during solar cycle 24 which exhibit characteristics features of magnetic clouds. Contribution of ejecta type ICMEs events is 20%, which is less than other type events.

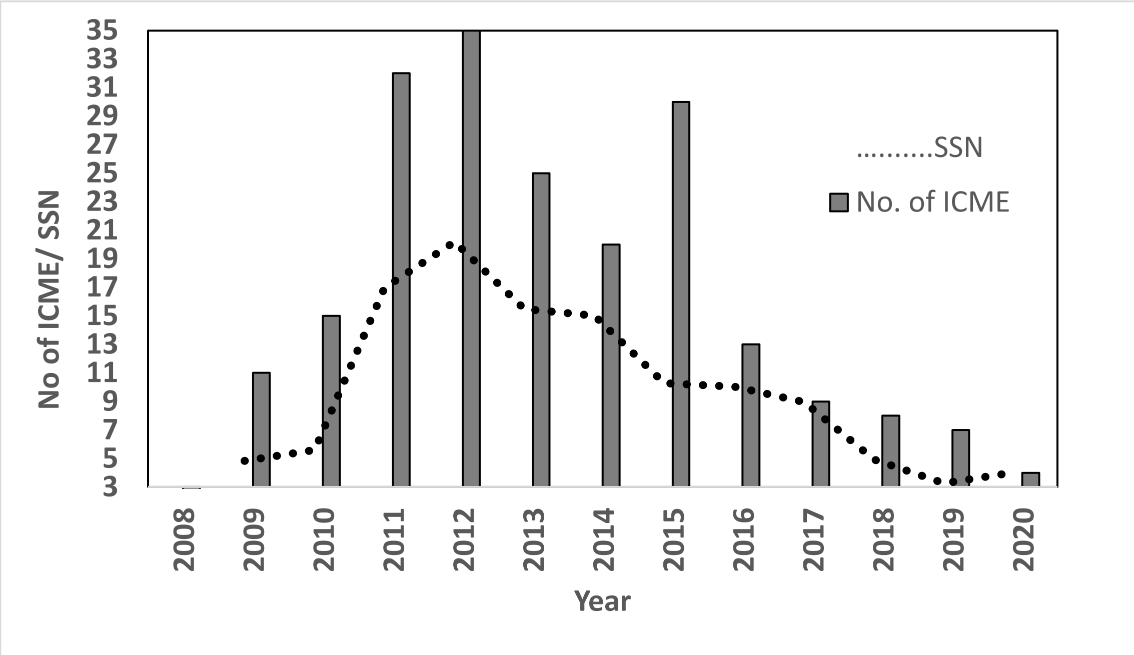

Figure 1- represents the yearly mean of sun spot number and yearly occurrence of ICMEs. Dashed line show sunspot number and ICMEs are presented by histograms.

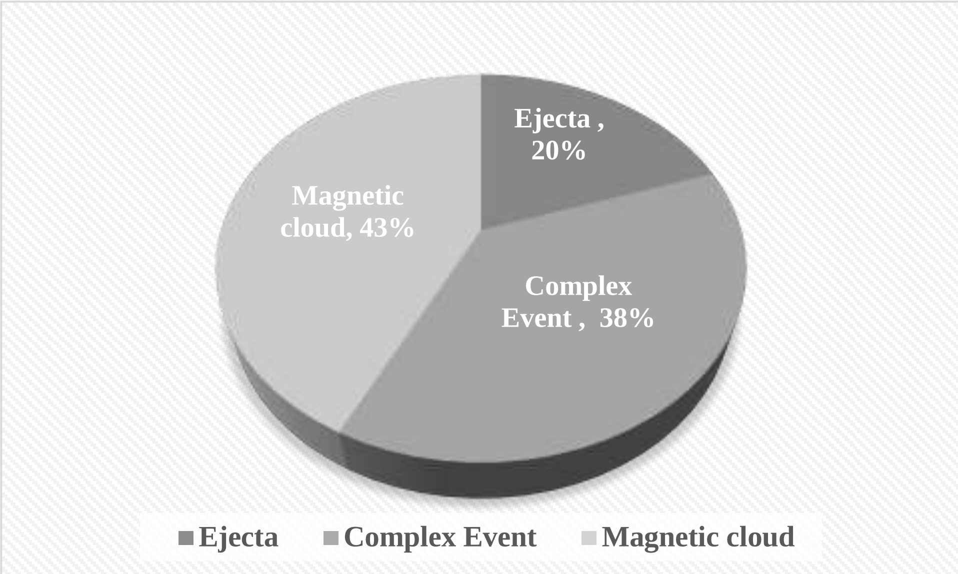

Figure-2 is a pie diagram to represent the % contribution of various subsets of ICMEs events during the period from 2009 to 2020.

3.1- Interplanetary Coronal Mass Ejections9ICMEs) and CRI Variation:

The average behavior of variation in % deviation of CRI with all ICMEs during the ascending and descending phases of solar cycle 24 is shown in figure .3 in which the zero day is corresponds to starting day of ICME event. we observed remarkable transient decreases in cosmic-ray intensity during both phases of cycle. The result of Chree analysis clearly predicts that the maximum decrease is observed one day after the onset of ICME. The magnitude of depression is found equal during ascending and descending phases. It is also seen that the recovery in CRI is faster during A>0 epoch of solar magnetic field i.e. descending phase of solar cycle.

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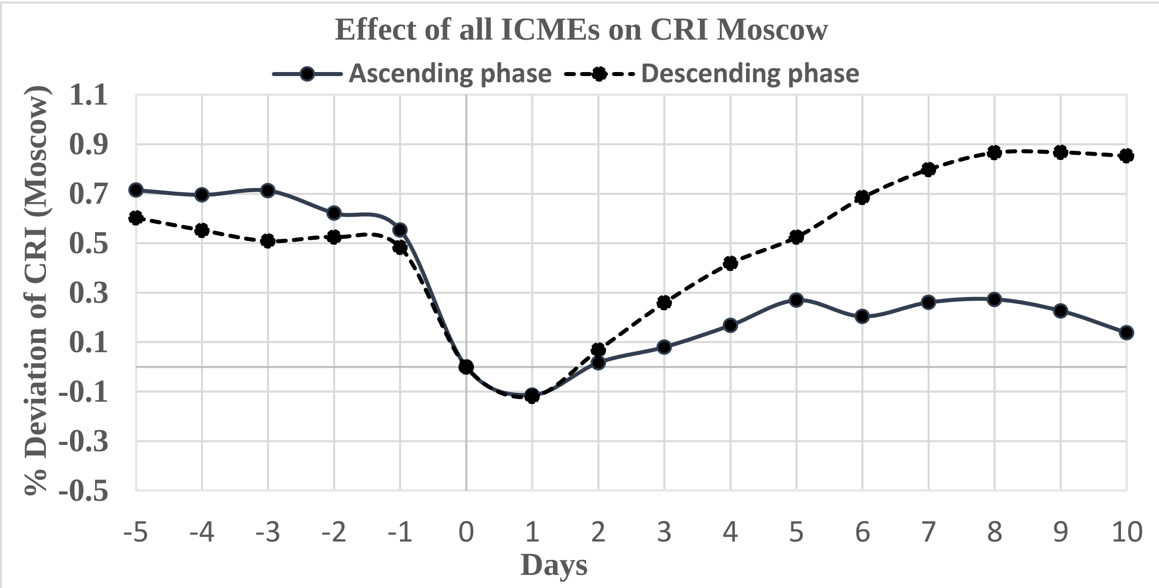

Figure 3. depicts the average behavior of percent deviation of CRI (Moscow) during ascending and descending phase of solar cycle with respect to zero epoch day. Zero day corresponds to starting day of near earth ICMEs (all).

We have done similar analysis to observed the effects of magnetic clouds, complex events and ejecta the subsets of ICMEs on CRI during ascending and descending phases of solar cycle 24 as shown in figure 4, 5 and 6 respectively.

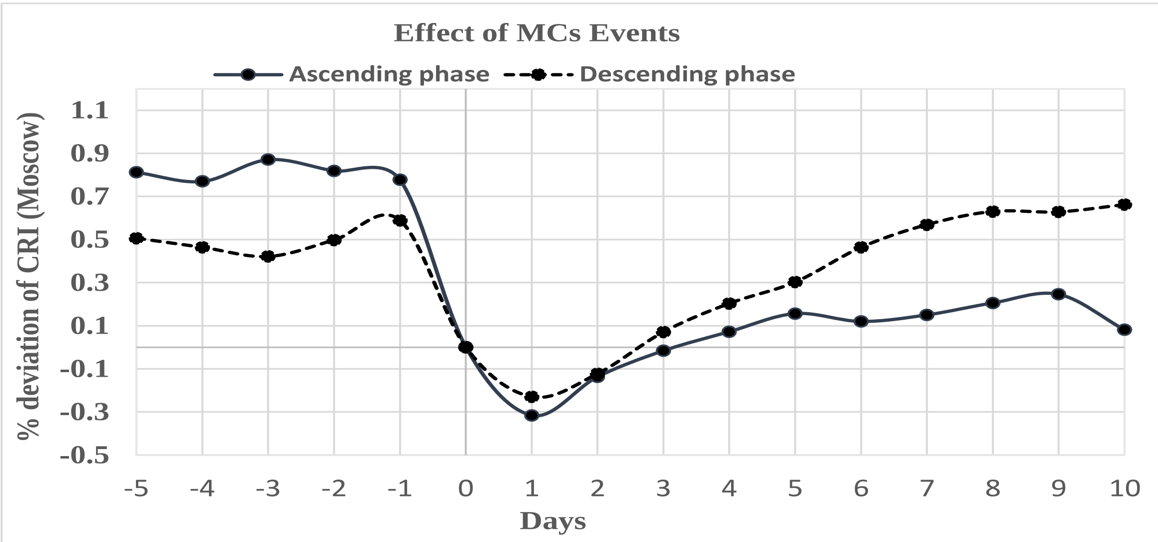

Figure 4. depicts the average behavior of percent deviation of CRI (Moscow) during

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ascending and descending phase of solar cycle with respect to zero epoch day. Zero day corresponds to starting day of MCs, a subset of near earth ICMEs.

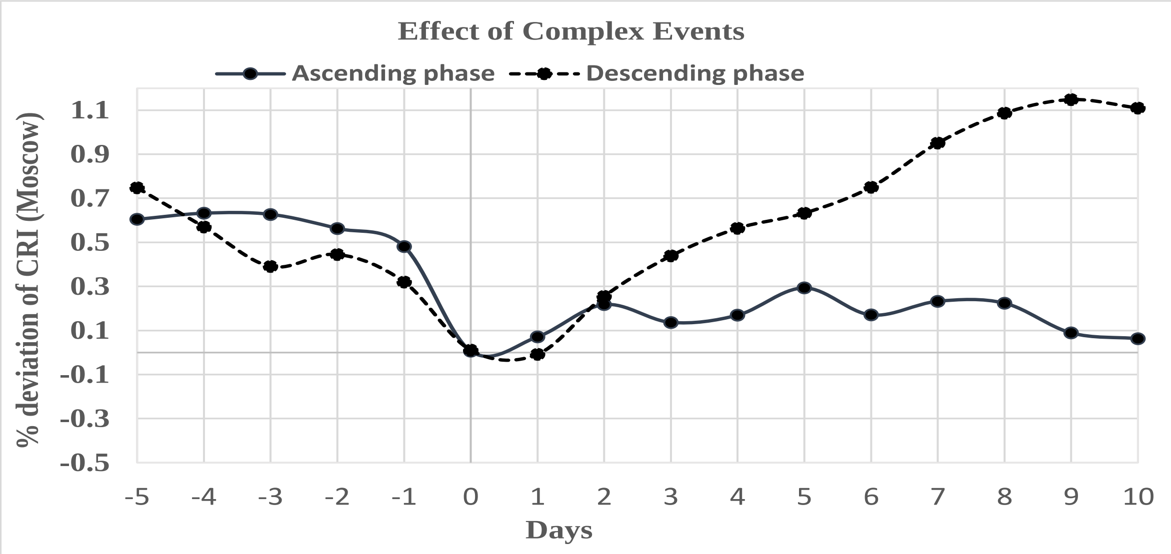

Figure 5. depicts the average behavior of percent deviation of CRI (Moscow) during ascending and descending phase of solar cycle with respect to zero epoch day. Zero day corresponds to starting day of complex events, a subset of near earth ICMEs.

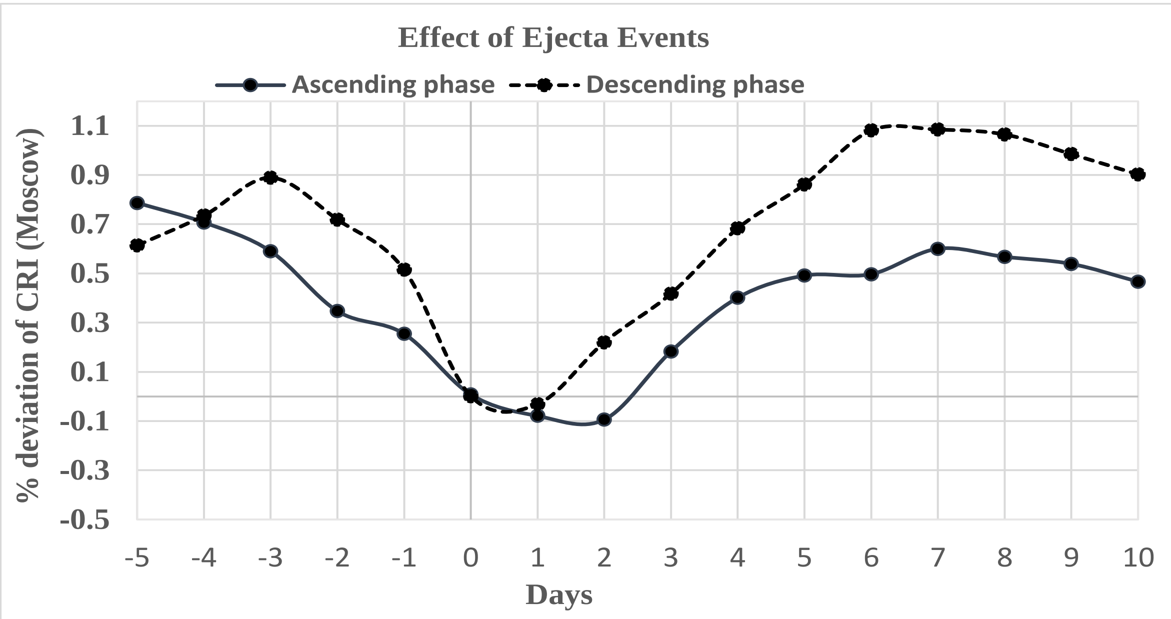

Figure 6. depicts the average behavior of percent deviation of CRI (Moscow) during ascending and descending phase of solar cycle with respect to zero epoch day. Zero day corresponds to starting day of ejecta(EJ), a subset of near earth ICMEs.

All types of ICMEs observed near earth produces significant decreases in CRI during both phases. However, the magnitudes of depression and variation profiles are found different for ICMEs of different character and changing from ascending to descending phase. ICMEs associated with MC structures produces maximum decreases and maximum depression is observed one day after the onset of event during both phases of cycle. Slower recovery is seen during ascending phase of cycle in comparison to descending phase due to effects of all types of ICMEs events. Complex events produces maximum decreases at the same day as onset, while ejecta events produces maximum decreases one day after the onset during descending phase and two days after the onset during ascending phase. Magnitude of Decreases in CRI is less produces by complex events but the temporal profile of CRI variation produces by ejecta is found symmetric in comparison to other events. Our findings suggest a significant role of ICMEs in short term modulation of cosmic ray. Often the ICMEs drive front shocks, the shock disturbances are highly effective in stimulating cosmic ray decreases. When a ICME is accompanied by a front shock, the compressed region is found between the shock and the driving ICME, which is also known as sheath region and play important role in producing decreases in CRI.

3.2 Interplanetary Coronal Mass Ejections and geomagnetic field variation:

Coronal Mass Ejections are equally effective in producing variations in cosmic ray intensity as well as disturbances in Earth's geomagnetic field. Hence it is essential to study the effects of ICMEs on activities of geomagnetic field. [Shrivastava et.al;2008] reported that ICMEs are capable in producing geomagnetic activity. They have investigated a decrease in Dst index and an increase in geomagnetic Ap index due to effect of ICMEs.. Presented work aims

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to examine the effects of ICME on geomagnetic activity by using the Ap and Dst indices of geomagnetic activity for the period of solar cycle 24.

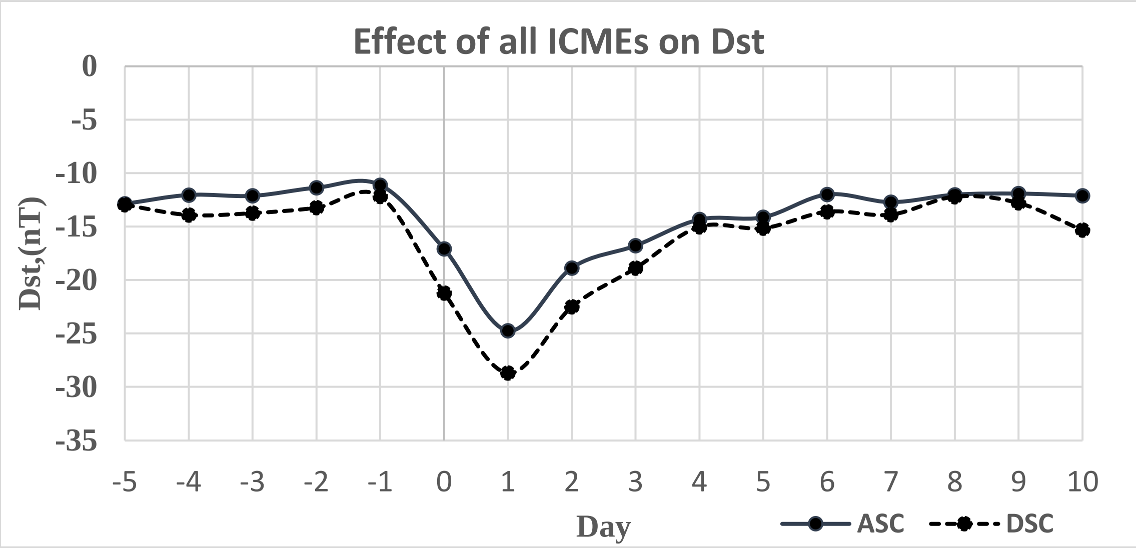

Figure.7 represents the variation of disturbance storm time (Dst index) with respect to zero epoch day .Zero day corresponds to starting day of ICMEs(all).Solid line shows variation during ascending phase and dotted line show variation during descending phase of solar cycle24.

Average behavior of variation in Dst index (geomagnetic activity parameter) with all ICMEs during the ascending and descending phases of solar cycle 24 is depicted in figure 7. The superposed epoch method of Chree analysis is applied to represent the variation of Dst index for a long time profile of -5 days to 10 days from zero day. Zero day is corresponds to onset of ICME.

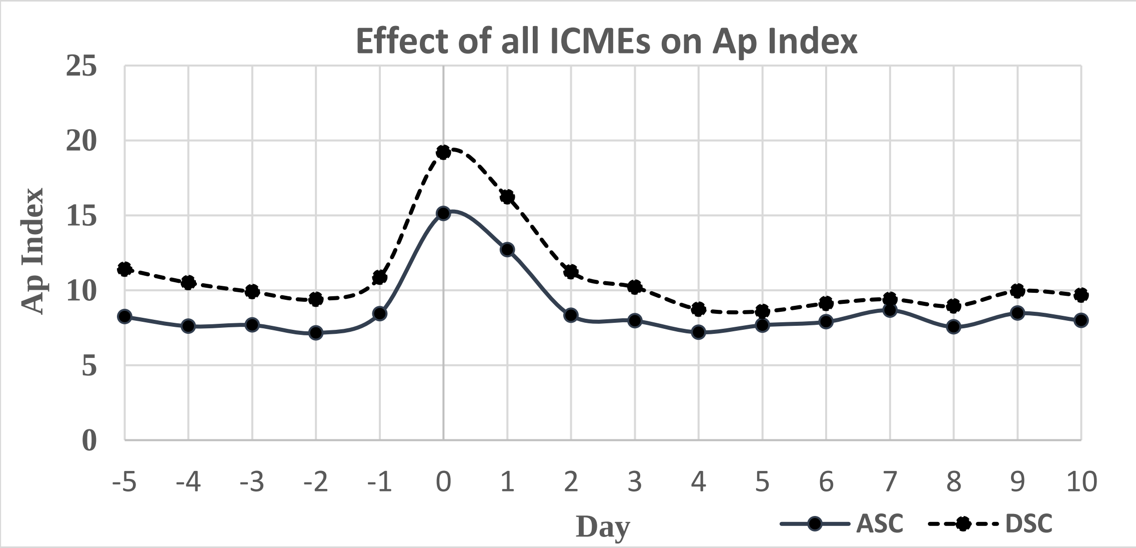

Figure.8 represents the variation in geomagnetic disturbance index(Ap index) with respect to zero epoch day .Zero day corresponds to starting day of ICMEs(all).Solid line shows variation during ascending phase and dotted line show variation during descending phase of solar cycle24.

A significant decrease is observed in Dst index for both phases of cycle and maximum depression is seen one day after onset of ICME for both phases. A clear difference can be seen between maximum decreases of ascending and descending phases. A similar picture is drawn to observe the average behavior in variation of Ap index from onset of ICME during ascending and descending phases of solar cycle as shown in figure 8.. Ap index shows remarkable, sharp increase at the same day at onset i.e. zero day for both cycle. Whereas ascending phase of cycle encounters the A<0 epoch and descending phase of cycle encounters the A>0 epoch of solar magnetic field, the maximum decrease in Dst index and maximum

enhancement in Ap index is found slightly greater during A>0 epoch in comparision to A<0 epoch of solar magnetic cycle.

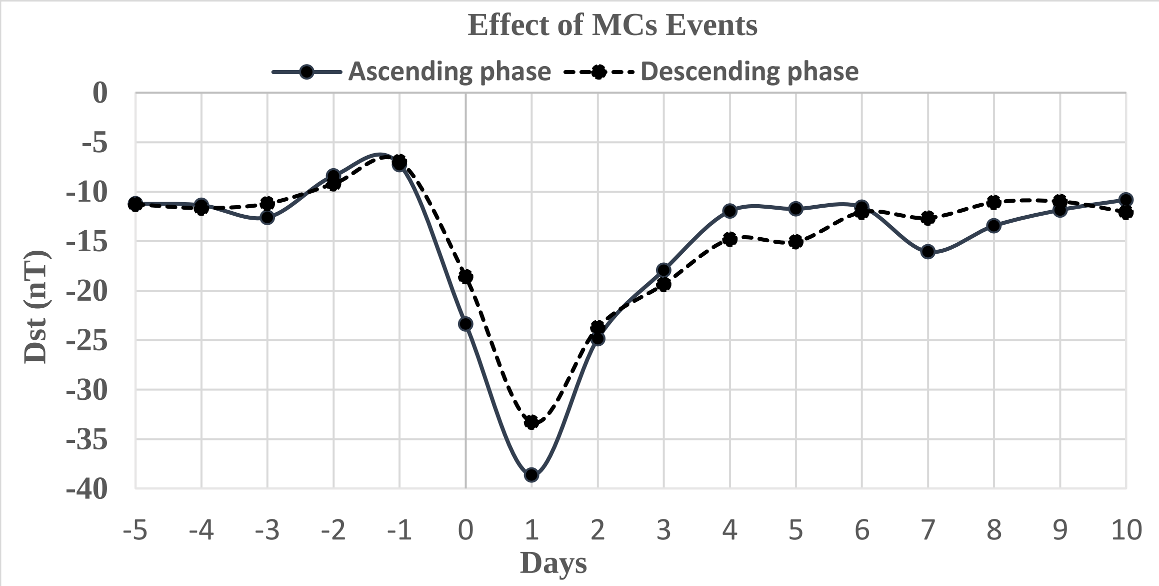

Figure.9 represents the variation of disturbance storm time (Dst index) with respect to zero epoch day .Zero day corresponds to starting day of MCs events, a subset of ICMEs. Solid line shows variation during ascending phase and dotted line show variation during descending phase of solar cycle24.

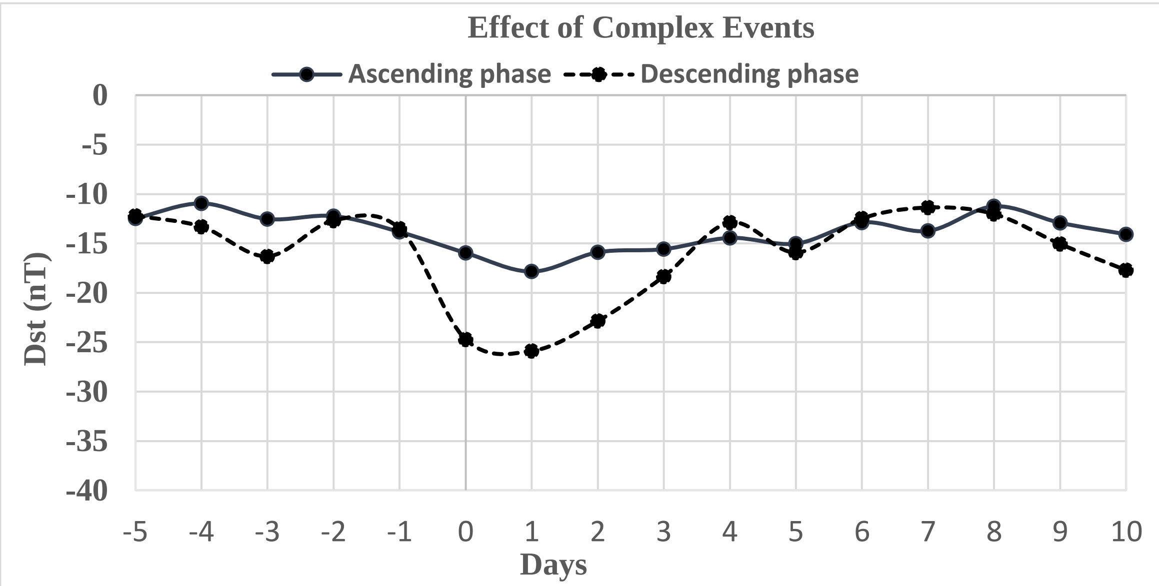

Figure.10 represents the variation of disturbance storm time (Dst index) with respect to zero epoch day .Zero day corresponds to starting day of complex events, a subset of ICMEs. Solid line shows variation during ascending phase and dotted line show variation during descending phase of solar cycle24.

Figures 9, 10 and 11 represents the variation in Dst index due to effects of MC type, complex events and ejecta subsets of ICMEs separately. A peculiarity is found in maximum decrease in Dst index due to effect of MC type ICMEs is that the maximum depression is larger during A<0 epoch. The variation profiles of Dst index due to effects of cmplex events and ejecta are found asymmetric.

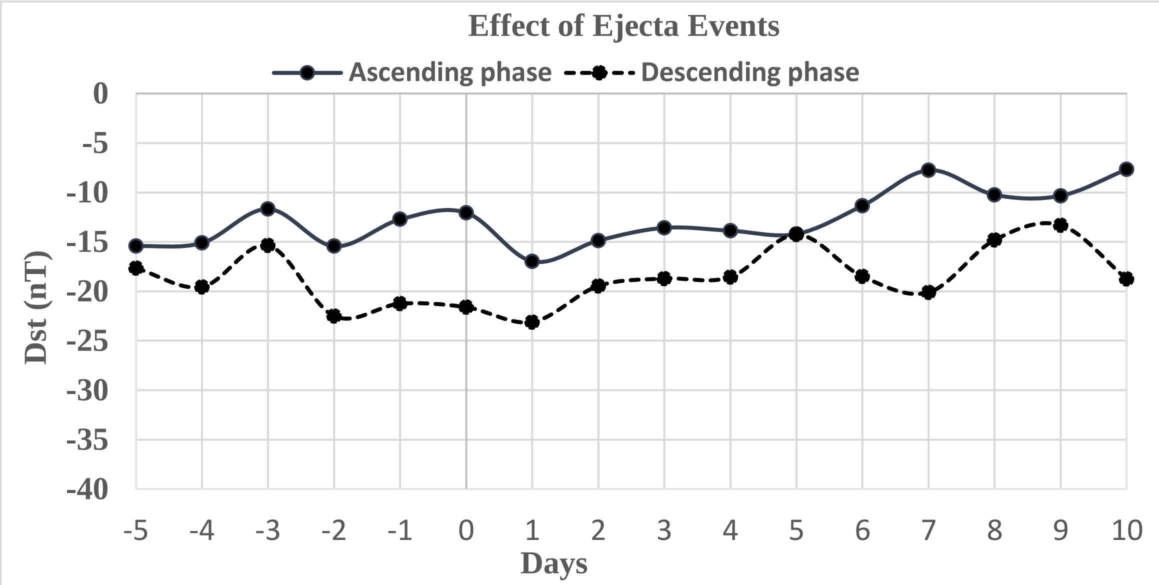

Figure.11 represents the variation of disturbance storm time (Dst index) with respect to zero epoch day .Zero day corresponds to starting day of ejecta (EJ)events, a subset of ICMEs. Solid line shows variation during ascending phase and dotted line show variation during descending phase of solar cycle24.

We have plotted the figures 12, 13 and 14 to show the variations in Ap index with various types of ICMEs. The results of Chree analysis indicates that the MC type ICMEs produces larger enhancements in Ap index and the temporal profiles of variation are about coincide and symmetric of both phases of solar cycle. In most of the cases the maximum variation is seen during A>0 epoch of solar magnetic field. The curves of Chree analysis to show the effect of ejecta on Dst and Ap index does not reflect clear results and represent many peaks in irregular manner.

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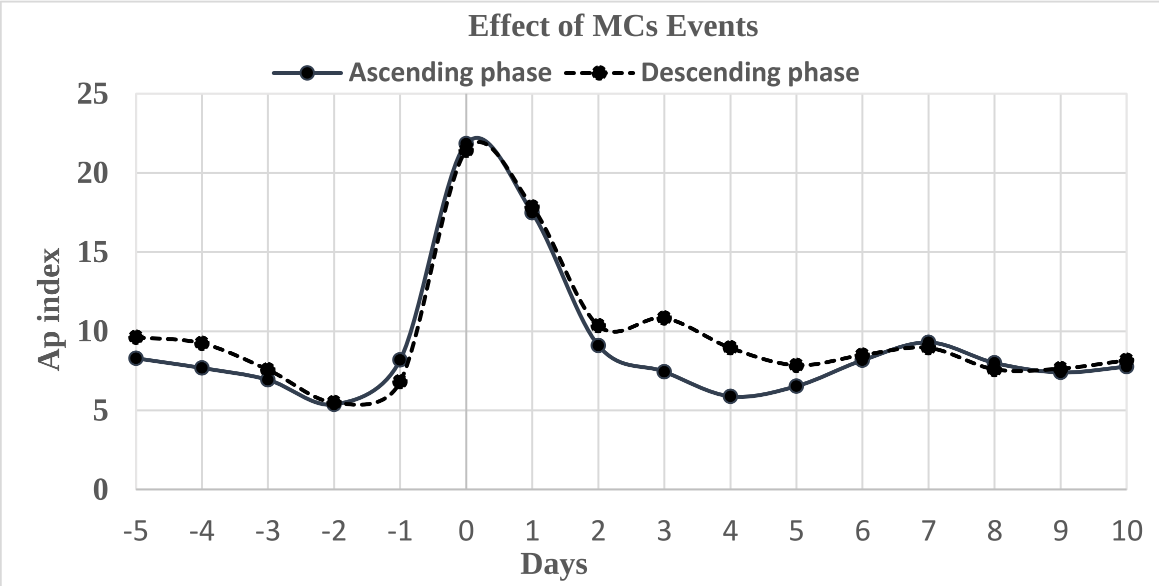

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Figure.12 represents the variation in geomagnetic disturbance index(Ap index) with respect to zero epoch day. Zero day corresponds to starting day of MCs events, a sub set of ICMEs. Solid line shows variation during ascending phase and dotted line show variation during descending phase of solar cycle24.

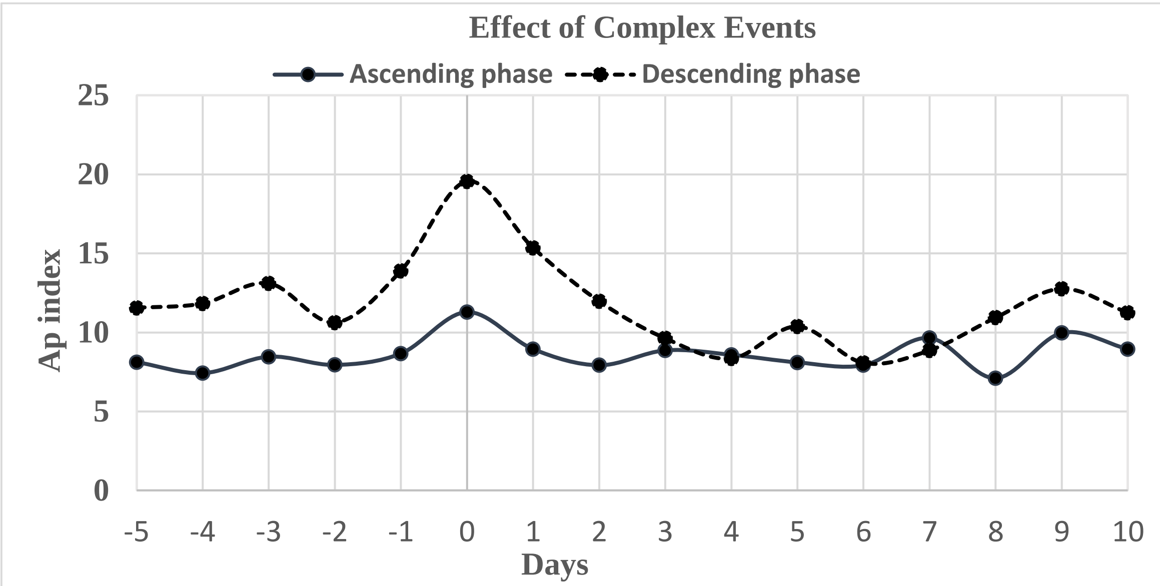

Figure.13 represents the variation in geomagnetic disturbance index(Ap index) with respect to zero epoch day. Zero day corresponds to starting day of complex events, a sub set of ICMEs. Solid line shows variation during ascending phase and dotted line show variation during descending phase of solar cycle24.

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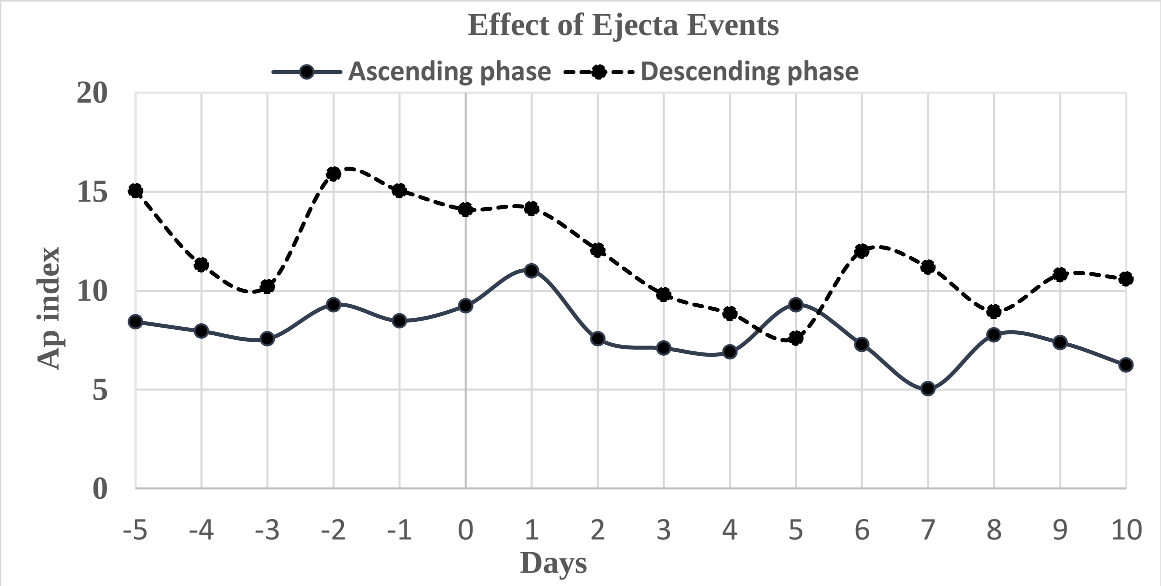

Figure.14 represents the variation in geomagnetic disturbance index(Ap index) with respect to zero epoch day. Zero day corresponds to starting day of ejecta (EJ)events, a sub set of ICMEs. Solid line shows variation during ascending phase and dotted line show variation during descending phase of solar cycle24.

3.3. Relationship of ICMEs Speed with CRI and Geomagnetic Activity:

To investigate the relationship of ICME speed with cosmic ray intensity and geomagnetic field, the ICME speed have been correlated with CRI , Dst index and Ap index as shows in Figure 15,16 and 17.

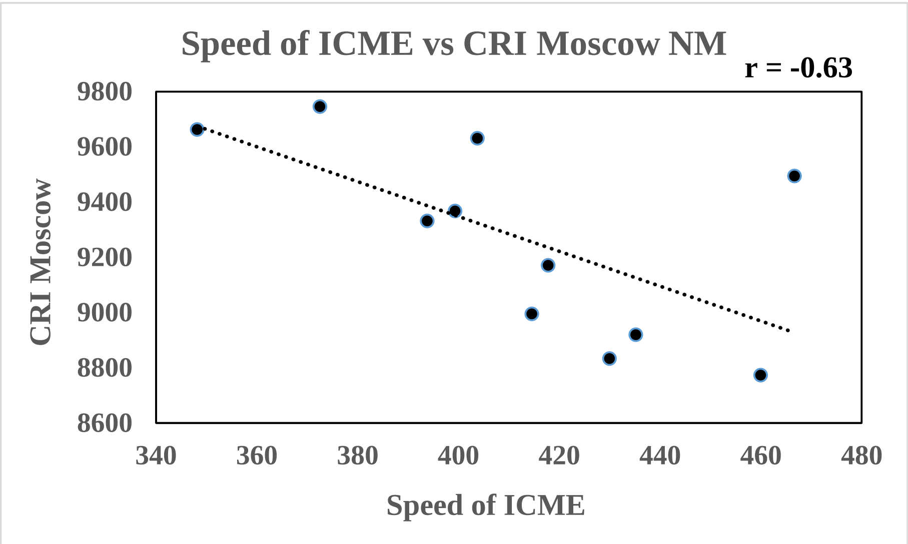

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Figure .15 shows the correlation graph between ICMEs speed and CRI during the period of (2009 to 2020)

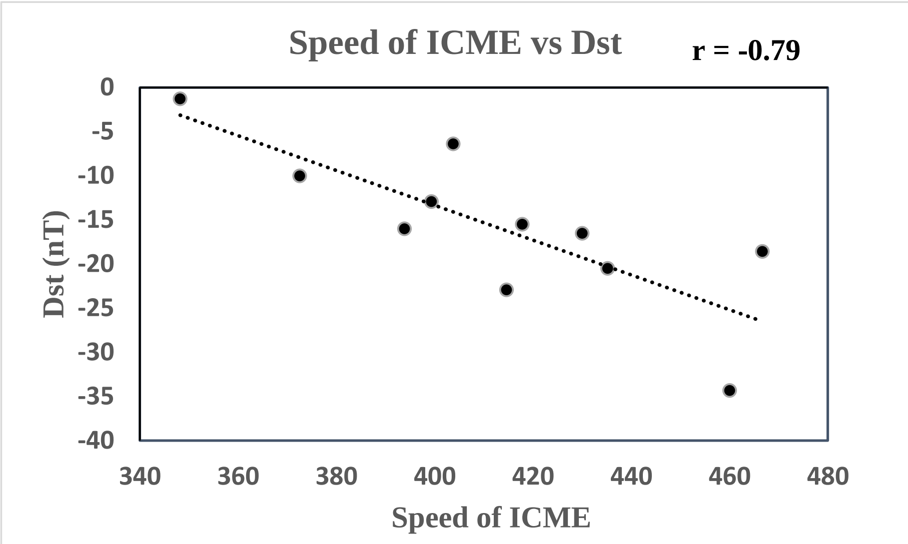

Figure .16 shows the correlation graph between ICMEs speed and Dst index during the period of (2009 to 2020)

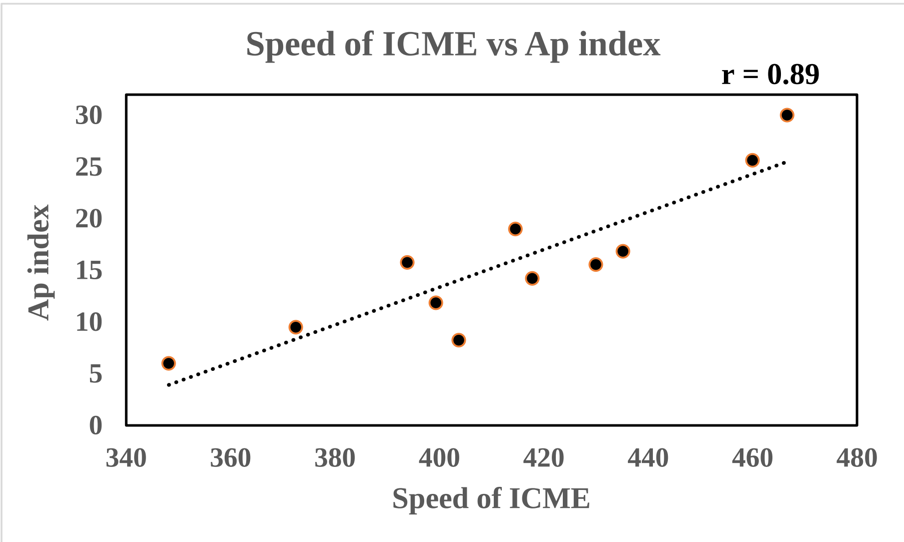

Figure .17 shows the correlation graph between ICMEs speed and Ap index during the period of (2009 to 2020)

Figure 15, 16 and 17 show the scatter graphs in which we have used yearly average values of ICMEs speed, CRI, Dst and Ap index. It is observed that a significant correlation is found between ICMEs speed and Ap index, which is high and positive. We also noted the correlation coefficients of speed of ICMEs with CRI and Dst index which is high and negative, which indicate the anti-correlationship between them.

A geomagnetic storm is started when interplanetary magnetic field (IMF) leads to an enhancement in earth ring current and large amount of energy is transferred from the solar wind. There are two physical mechanisms which determine the geomagnetic storm strength. First, ram pressure of solar wind near the magnetopause, which is expressed by $(ev^2)sw$, where, e is the main density and v is the vertical speed of solar wind and Second the direction of the Z-component of IMF. Southward direction of Z-component of IMF for long time produces the magnetic reconnection between geomagnetic field and IMF. This makes possible the injection of plasma particles of solar wind into earth ring current.[Briend et al.2000] reported that the ring current decay lifetime changes with VBs and this does not depend on Dst. A compressed southward field linked with fast stream and enhanced dynamic pressure in solar wind are responsible to create the N –S polarity clouds, which in turn increase in geo- effectiveness [Fenrich et.al;1998].

The study has importance for space weather variations and their effects on climate change on earth.

4. Conclussions:

It is concluded from the present analysis that:

1. The ICMEs events associated with characteristics of magnetic cloud are found larger during the study period. 209 events of ICMEs detected, out of which 89

events (43%) are MC type events which have enhance magnetic field > 10nT and rotate smoothly with large angles.

2. Occurrence of ICMEs follows the pattern of sun spot number which reveals that the no. of ICMEs can be used as a reliable solar parameter.

3. All types of ICMEs produces Significant decreases in CRI and Dst index, While creates enhancement in Ap index.

4. The ICMEs associated features of magnetic clouds produces larger variations in CRI, Dst and Ap index than others.

5. It is also concluded from the study that the overall effect of all ICMEs on CRI, Dst index and Ap index is slightly larger during the descending phase of solar cycle 24, which encounters during A>0 epoch of solar magnetic field. A peculiarity is found that the maximum depression in Dst index is observed during ascending phase of solar cycle due to effect of magnetic cloud type events because of occurrence of Magnetic Cloud type events was more during ascending phase.

6. The maximum depression in CRI and Dst index due to effect of ICMEs is observed one day after the onset, the maximum enhancement in Ap index is found at zero epoch day i. e. starting day of events in most of the cases. We may conclude that the effects of ICMEs on Ap index are quick and very fast.

7. CRI is decreases due to effect of ejecta type events but there is no remarkable effect is seen on geomagnetic activity due to these events.

8. The correlation coefficient of ICME speed with Ap index is found high and positive, while the correlation coefficients of speed with CRI and Dst index is

noted high and negative, which establish the significant roll of ICMEs speed in CRI variation and in producing geomagnetic activity.

5. Acknowledgement: Authors are thankful to website managers of omniweb, Moscow NM and newly updated catalogue of ICMEs compiled by Richardson and Cane for maintaining and uploading the updated data on websites and made their data available for analysis. The authors are also thankful to the referees for their valuable suggestions.

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