MODULATION OF COSMIC RAYS IN RELATION WITH SOLAR AND INTERPLANETARY DISTURBANCES

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ABSTRACT

In this work, we analyze the long-term cosmic-ray modulation observed by the high counting rate neutron monitor, which is the detector with the longest cosmic-ray record, from 1965. In this analysis we have used the yearly mean values obtained from the different neutron monitors located at various parts of the world. In this paper we have correlated CRI of Neutron Monitors stations of different cut off rigidity and SSN for the period 1996 to 2014. We choose three stations having high, middle and low cut off rigidity situated at various locations on the surface of the Earth. Concluding, we have shown that here is a systematic difference in cosmic ray intensity cyclic evolution of odd and even cycles which is ascribed to the possible role of drift effects in heliospheric modulation of cosmic rays.

Keywords: Cosmic Ray, Long-Term Relation, Interplanetary Disturbances, Sunspot No.

INTRODUCTION

Cosmic rays are high-energy charged particles that originate in space and travel at almost the speed of light to the Earth. Almost all cosmic rays are composed of nuclei of atoms from the lightest to the heaviest elements in the periodic table. They are called "galactic" because they come from origins outside the solar system and spread over the Milky Way. They also contain energetic particles such as nuclei and electrons that have been accelerated by energetic events in the Sun and interplanetary space and have an energy spectrum ranging from 100 MeV to 10 GeV within the Milky Way.

Variations in cosmic-ray intensity have been measured continuously since 1936, with intermittent data prior to that. The Carnegie Institute of Washington funded the creation of a "precision recording cosmic-ray metre,"[1] five of which were deployed in the United States, Mexico, Peru, New Zealand, and, subsequently, Greenland. Data from these devices were extensively disseminated, demonstrating that cosmic-ray intensity in the 3-20 GeV range is under short-term (monthly) and long-term (11-year) solar influence.[2]

John Simpson invented the neutron monitor (NM) in 1951, and by the International Geophysical Year (IGY) in 1957, more than 50 NMs had been placed throughout the world.[3]

In the 1960s, larger "super-NMs" replaced the originals, and a global network of over 40 instruments is now in operation.[4] Prior to 1936, there were many high-altitude, well-calibrated ionisation chamber readings that allowed us to go back to the 1933 sunspot minimum. As a result, we now have high-resolution data of cosmic-ray intensity at Earth over the last eight solar cycles, from 1933 to 2019. Beginning in 1965, satellite and spacecraft measurements supplemented these observations. Furthermore, observations of the yearly cosmogenic radionuclides ^{10}Be and ^{14}C from 1389 show that the 11-year modulation of cosmic radiation was present during the whole era.[5]

Short-term decreases in galactic cosmic ray (CR) flux are caused by changes in solar parameters such as proton speed, density, and temperature, as well as dynamically fluctuating compressions of the interplanetary magnetic field (IMF). Because they were initially described by Forbush, these depressions are commonly referred to as Forbush declines (FDs).[6]

Forbush decreases were related to solar activity by Simpson.[7] They are categorised as interplanetary coronal mass ejections (ICMEs) or corotating interaction zones based on their nature and origin (CIRs). Interplanetary coronal mass ejections (ICMEs) are the interplanetary counterparts of coronal mass ejections (CMEs), which are powerful eruptions of coronal magnetoplasma travelling through the heliosphere, whereas CIRs are related to high-speed solar-wind streams originating in low-latitude coronal holes. Because the pattern of the SW and IMF disruptions differs, these two phenomena may be easily distinguished in in-situ measurements.[8-11]

In this regard, we observe that the combination of these two phenomena results in the development of complex occurrences that comprise a distinct class of SWDs.[12] There is evidence that the processes through which various forms of SWDs cause CR depressions differ. Previous research has demonstrated that ICMEs cause occasional severely asymmetric depressions, whereas CIRs cause repeated, more symmetric, and shallow depressions. Furthermore, when a shock forms at the leading edge of the disturbance, the depressions tend to be deeper, resulting in a two-step drop. [10,13,14,]

Because the shock-sheath area is characterised by a highly changing magnetic field, which decreases the CR diffusion length, this suggests that decreased diffusion plays an essential role in reducing the CR flux. Indeed, the majority of theoretical models for CR transport highlight the relevance of pitch angle scatter and magnetic field variations, both for galactic and solar cosmic rays.[15-20]

Along with diffusion, CRs are modulated by several other effects: convection by solar wind, gradient and curvature drift, and energy loss,[21] where the last one is usually considered as negligible for high-energy particles ($E > 1$ GeV).[15]

Regarding the two-step FDs caused by ICMEs, the reduced diffusion model is thought to be appropriate for the shock-sheath region, whereas the exclusion of CRs because of the ejection itself is suspected to be caused by their closed magnetic field structure.[22]

Two-step FDs are in the focus of several recent studies, especially those that are associated with magnetic clouds.[23] They are not only the most prominent events, showing highest depression amplitudes[10], they are also found to be useful in unrevealing the internal structure and geometry of ICMEs.[24-25]

From the observational point of view, the influence of CR modulation was previously investigated through a number of studies employing the superposed epoch analysis [13-14,26-27], statistical analysis.[12,17,28-31]
The results were frequently mutually conflicting, and consequently did not provide a clear empirical bacground. The correlation between the depression amplitude and some CIR parameters was found by Richardson and Calogovi et al..[17,29]
Richardson pointed out that the SWD speed might be the most important parameter, favoring a diffusion-convection model for this behavior.[17] On the other hand, Calogovi et al. found a statistically significant correlation between the depression amplitude and the SWD magnetic field strength, which is more in favor of the diffusion drift model proposed by Kota & Jokipii.[16,29]
Similar inconsistencies were found in studies of ICMEs. For example, Cane etal declared speed as a poor predictor of depression amplitude,[28] whereas Chilingarian & Bostanjyan found a strong correlation between the two.[30] Another aspect of CR modulation, the time profile, was found to be related to the speed for both CIRs[26] and ICMEs [13,32], but some questions still remain open.[31,33]

SOLAR COSMIC RAYS

The Sun is known to produce particles locally, which can be termed as solar cosmic rays (SCRs). Dorman and Venkatesan has been reported many important aspects about SCRs.[34] These rays were firstly discovered experimentally on 28 February 1942, as a sudden increase of Geiger counters counting rate. The counting rate was associated with a large solar flare. Since that time detectors, set up to monitor cosmic rays, have occasionally seen sudden increases in the intensity of the radiation (sometimes as large as several hundred per cent) associated eight outbursts on the Sun, mostly with visible flares. The chemical composition of these radiations has been found to vary greatly from event to event. The CRI returns to normal within tens of minutes to hours, as the acceleration process ends and as accelerated ions disperse throughout interplanetary space. The short increases of CR detectors count rate associated with solar particles arrival are called GLE (Ground Level Enhancement). The energies of such particles are less than 100 MeV but sometimes it can be much higher than 1 GeV. Fig .1 shows solar cosmic rays with energy band gap.

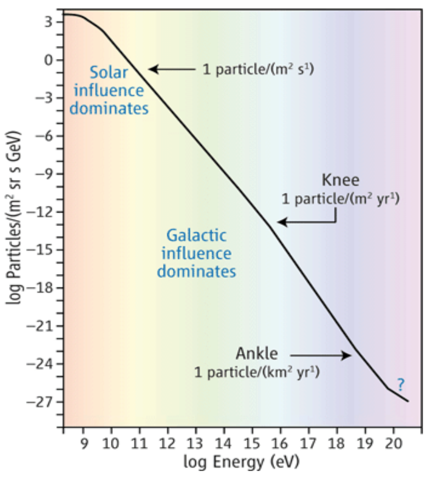

Fig 1 solar cosmic rays with energy band gap

SCRs were first detected from an inspection of data obtained by worldwide CR monitoring stations. At energies > 100 MeV/nucleon, the relative composition of SCRs is about the same as of solar atmosphere. While at low energy range there is a tendency to enrich the radiations by heavy and very heavy nucleus and these increases as the energy decreases. Solar cosmic rays have helped in the study of electromagnetic conditions in the solar atmosphere. Because of their proximity of origin these solar energetic particles have generated exceptional interest of the researchers. A third component of CRs, comprised of only those elements that are difficult to ionize, including He, N, O, Ne, and Ar, was given the name "Anomalous cosmic rays" because of its unusual composition. Anomalous cosmic rays originate from electrically-neutral interstellar particles that have entered the solar system unaffected by the magnetic field of the solar wind, been ionized, and then accelerated at the shock wave formed when the solar wind slows as a result of flowing into the interstellar gas, presently thought to occur somewhere between 75 and 100 AU from the Sun (one AU is the distance from the Sun to the Earth). Thus, it is possible that the Voyager 1 spacecraft, which should reach 100 AU by 2007, will have the opportunity to observe an example of cosmic ray acceleration directly.

INTENSITY VARIATION OF COSMIC RAYS

As we know that intensities of GCRs are moderated upon entering the heliosphere, these variations are defined as solar modulations. Solar modulations of these rays are categorized as long-term or transient modulations based on their durations. These variations have been correlated by studies with the characteristics of the solar wind and the interplanetary magnetic field. Various researches have been done on various aspects of cosmic ray time variations.[35-41]

In recent years, the subject of time variations of CRs has grown in importance, with increasing awareness that it will unlock mysteries to the origin of CR and of the electromagnetic fields in interplanetary and interstellar space. The close relationship of many of the variation with events occurring on the sum is of great interest in the understanding of solar physics. Elliot did a comprehensive review of the status of knowledge concerning CRI variations and categorised them as:

1. Short-term variation
2. Solar diurnal variations
3. Semi-diurnal variations
4. Tri-diurnal and Quart diurnal variations
5. 27–day variations
6. Forbush Decreases
7. Long-term variation
8. 11/22- year variation

ORIGIN OF COSMIC RAYS

Although presence of penetrating radiations and their cosmic nature were discover in 1900-1901 by Wilson, Geitel and Elster. Hess observed an increase of ionization with altitude. He concluded that the radiation came from outside the atmosphere.[42]

He observed that the radiation was equally strong in day and night time, hence suggesting its non-solar origin. These are relativistic and mostly charged particles bombarding Earth's atmosphere from the outer space. They originate outside the Earth, but because of a distortion of their trajectories by chaotic magnetic fields in interstellar space their arrival directions do not point back to their site of origin. Nevertheless they bring important information about very energetic processes in the Universe and about the sources, interstellar space and magnetic fields. The observation of these rays helps to explore the Universe and to reveal some of its mysteries. An explanation of the origin and nature of the most energetic CRs is important not only to astronomers, but also to particle physicists. Their efforts are now united in rapidly evolving new field of scienceastroparticle physics.

METHOD

The interplanetary medium and the terrestrial magnetic field respond to most of solar parameters and their evolution. Fig. 2 shows cosmic ray intensity of number of solar flares of all three categories (Normal, Faint and Bright) for the period 2010 to 2020**.** Cosmic ray neutron data are available for almost six decades and the data from high counting rate neutron monitor exist only from 1965. In this analysis we have used the yearly mean values obtained from the different neutron monitors located at various parts of the world. We can see from the figure that large number of SFs and SSNs occurred during the high solar activity period of solar cycle 23 while CR counts are low.[43]

Number of SFs and SSNs are low during the low solar activity period of the solar cycle and cosmic ray counts are higher.

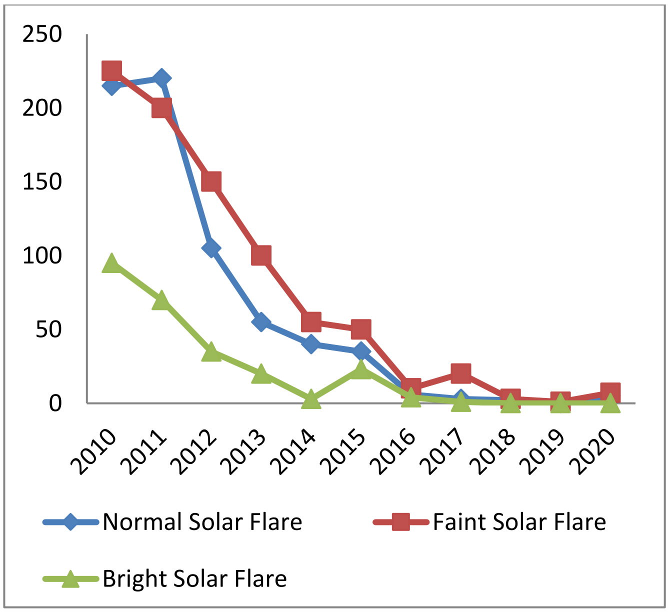

Fig. 2 Cosmic ray intensity of number of solar flares of all categories (N, F and B)

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DISCUSSION

In this paper we have correlated CRI of Neutron Monitors stations of different cut off rigidity and SSN for the period 2000 to 2014. We choose three stations having high, middle and low cut off rigidity situated at various locations on the surface of the Earth.

Fig 3 shows Sunspot Number and Fig 4 show Cosmic Ray Intensity of Neutron Monitor Station (Cut off rigidity, 2.46 GV) for the period 2000 to 2014. Cosmic ray intensity is highest in 1996 and decreasing in 2001 to 2003 and started increasing till 2008-2009 for solar cycle 23. As the new solar cycle 24 started the value of cosmic ray intensity is decreasing till date.

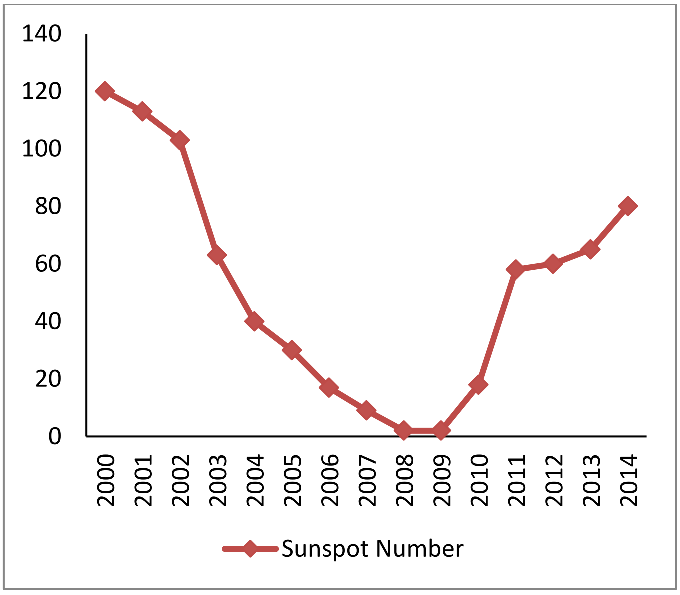

Fig 3 Sunspot Number

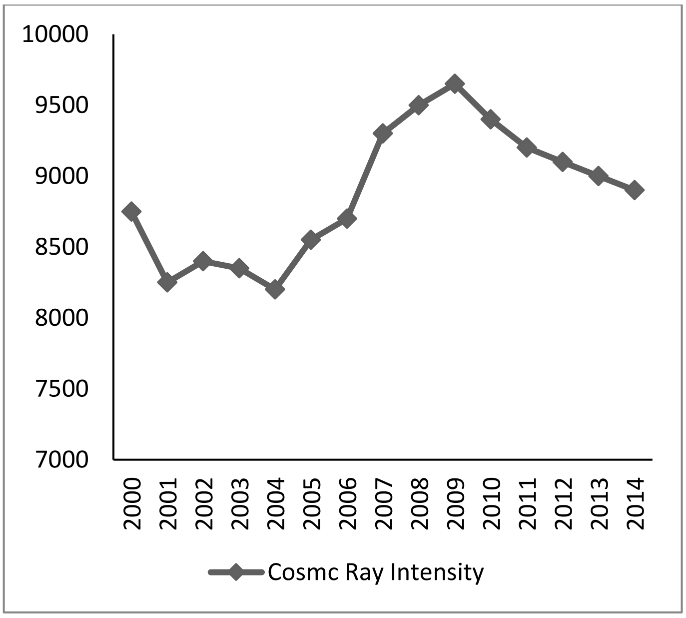

Fig 4 Cosmic Ray Intensity (Cut-off rigidity, 2.46 GV)

Fig 5 shows Cosmic Ray Intensity of Neutron Monitor Station (Cut off rigidity, 10GV) for the period 2000 to 2014. From 2003 to 2008 there are some peaks and deeps in the graph which is maximum variation in the cosmic ray intensity.[44]

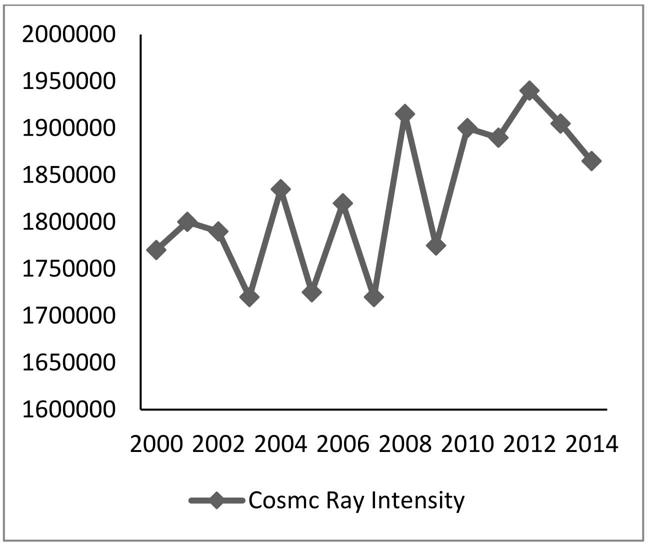

Fig 5 Cosmic Ray Intensity (Cut off rigidity, 10GV)

Fig 6 shows Cosmic Ray Intensity of Neutron Monitor Station (Cut off rigidity, 9.56 GV) for the period 2000 to 2010. Cosmic ray data is not available after 2010. For solar cycle 24, the Sunspot number shows decreasing phase from 2001 to 2008. At the same time cosmic ray intensity (CRI) shows increasing phase from 2001 to 2008. Thus it is clear from figure that for cycle 24 Sunspot activity and cosmic ray intensity (CRI) are anti-correlated. But general it is seen that the maximum / minimum of Sunspot number do not coincide with minimum / maximum of cosmic ray intensity.

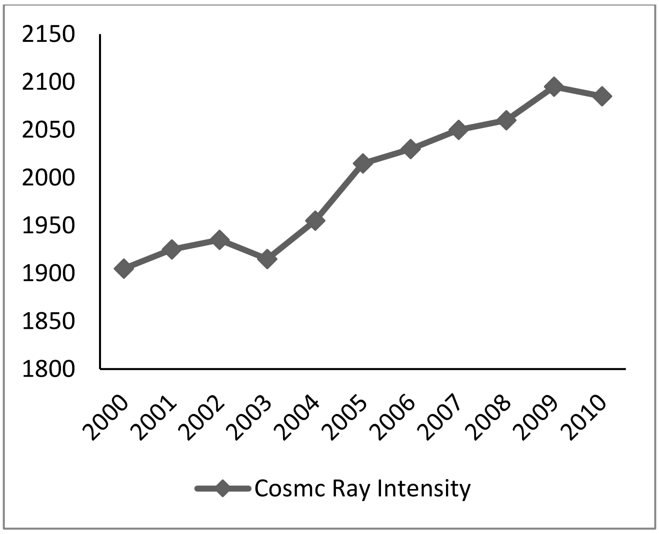

Fig 6 Cosmic Ray Intensity (Cut-off rigidity, 9.56 GV)

All the three graphs show clear anti correlation between cosmic ray intensity and Sunspot number. Neutron monitor situated at high latitude (Cut off rigidity, 2.46 GV) observed large number of cosmic ray particles and larger deviation in the yearly values of cosmic ray data from one year to another year.

Neutron monitor situated at low latitude (Cut off rigidity, 9.56 GV) observed comparatively less number of cosmic ray particles and small variation in the yearly values of cosmic ray data from one year to another year. Using yearly mean values of Sunspot numbers and cosmic ray intensity, the correlation coefficient have been derived for the three solar cycles 22, 23 and 24 for this purpose cosmic ray data of three neutron monitors, which are located at various parts of the world, have been used. We have calculated correlation coefficient for this and found different values of correlation coefficient (r) for the three stations.

Fig. 7,8 & 9 shows Ap index, solar wind velocity & cosmic ray intensity (cut off rigidity, 2.56 GV) for the period 2000 to 2014. It's clear from the graphs that Sunspot number and Ap are highly correlated whereas cosmic ray intensity & Sunspot numbers are anti- correlated and solar wind velocity and Sunspot numbers show negative correlation.

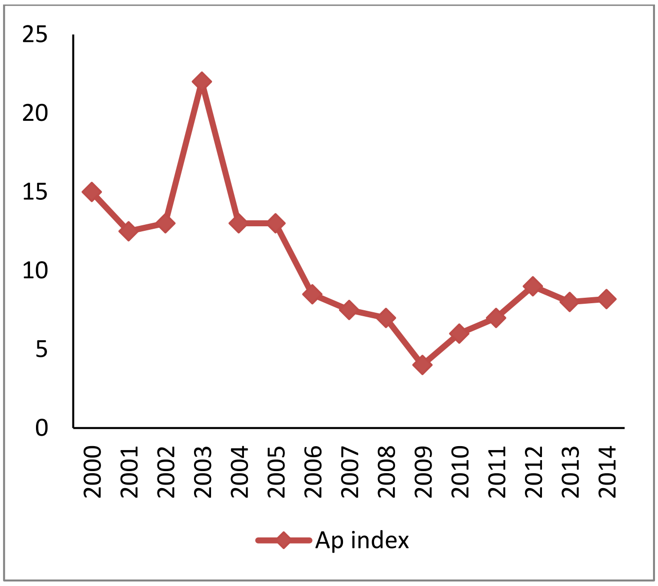

Fig. 7 Ap index (cut off rigidity, 2.56 GV)

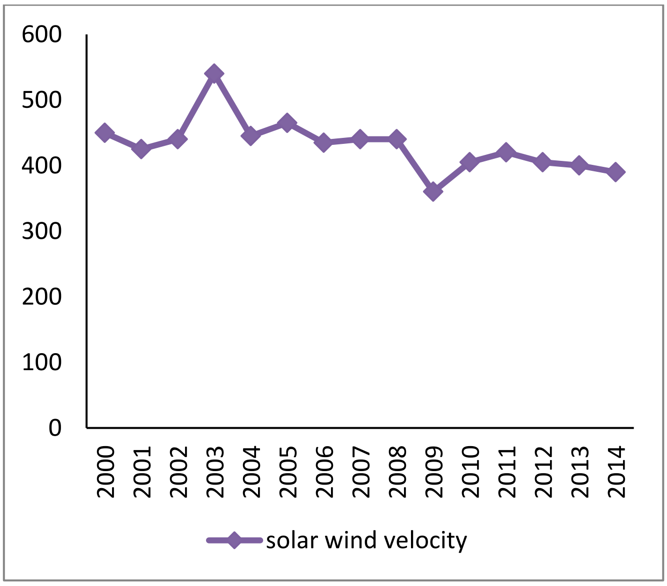

Fig. 8 solar wind velocity (cut off rigidity, 2.56 GV)

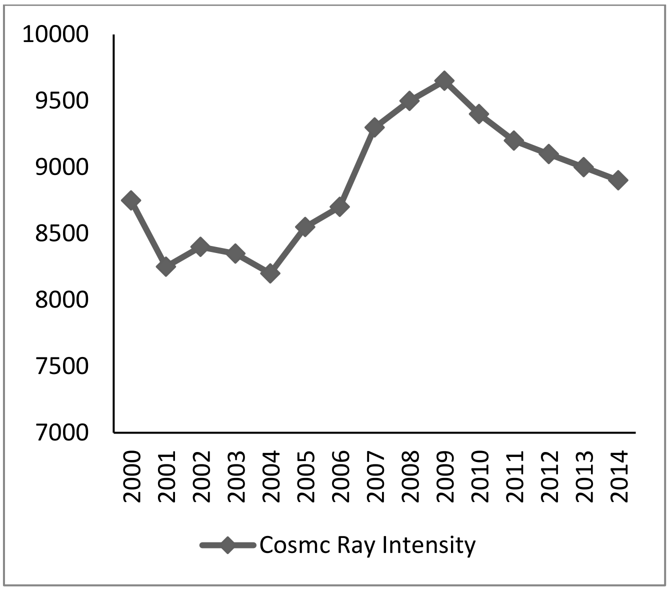

Fig. 9 cosmic ray intensity (cut off rigidity, 2.56 GV)

CONCLUSONS

Concluding, we have shown that here is a systematic difference in cosmic ray intensity cyclic evolution of odd and even cycles which is ascribed to the possible role of drift effects in heliospheric modulation of cosmic rays. The odd CR cycles are longer than even cycles and the momentary time lag between equal phases of cosmic ray and Sunspot activity cycles is large for odd cycle and small or negative for even cycles. The minimum value of Ap in a cycle is related to the amplitude of the following SSN cycle. Ahluwalia used this insight to develop a methodology for predicting key parameters for the peak of cycle 24. It provided one of the very few successful predictions for the amplitude of cycle 24. The overall behaviours of different parameters are same. The result may provide new light regarding cosmic ray modulation in association with Ap, SSN and SF. The degree of correlation of cosmic rays with all parameters during different solar cycles will highlight the dynamics of cosmic ray propagation. It was reported that the behaviour of solar cycle 24 is different from that of solar cycle23.

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