Abstract

Large-scale structures in the solar wind *i.e.* interplanetary coronal mass ejections, interplanetary shocks, magnetic clouds, corotating interaction regions etc., have been identified in the inner heliosphere near-Earth space using space-based and ground-based observations. Continuous observations of these structures and solar-wind plasma/field parameters are available at least for solar cycle 23 (1995 – 2009) and later periods. Simultaneous ground-based cosmic ray data by neutron monitors (NMs) located at different latitudes and longitudes is also being recorded worldwide. In this work, we concentrate on the study of large-scale structures in the inner heliosphere and their effects on the cosmic-ray intensity and simultaneously on solar-wind parameters.

In the heliosphere, the large-scale structure of the solar wind is dominated by two types of interplanetary disturbances: transient and corotating disturbances. Corotating disturbances, associated with spatial variability and solar rotation, occur in response to the interaction of fast and slow solar winds. Transient disturbances, due to episodic solar eruptions, expand outward from the Sun into interplanetary space. Interplanetary structures such as shocks, sheaths, interplanetary counterparts of coronal mass ejections (ICMEs), magnetic clouds, and corotating interaction regions (CIRs) are of special interest for the study of the transient modulation of galactic cosmic rays (GCRs). Depending on their associated features, the ICMEs identified in near-Earth space are grouped into the different classes; *i.e.* ICMEs may or may not be associated with shock/sheath, bidirectional superthermal electron event (BDE), magnetic-cloud (MC) structures, and halo CME structure. Further, BDE-ICMEs are divided on the basis of their occurrence with bidirectional energetic ion flows (BIF) and without BIF signatures. These structures modulate the GCR intensity with varying amplitude and recovery-time profiles. This classification into different groups lead us to study in detail the relative GCR-effectiveness (*i.e.* ability to depress GCR intensity) of different structures/features associated/not-associated with ICMEs. It will help us not only in identifying the structures/features of importance but also to understand the physical mechanisms playing important roles in transient modulation of galactic cosmic rays. A Forbush decrease is characterized by rapid reduction in cosmic-ray intensity within one to two days followed by a slow recovery typically lasting several
days. It is known that ICMEs are mainly responsible for Forbush decreases in GCR intensity. However, not all of the ICMEs produce such decreases in GCR intensity.

For the statistical study of the GCR-response to these ICMEs, based on the degree of their “effectiveness” (we call it “GCR effectiveness” more precisely) in producing depressions in GCR intensity, we have divided ICME “GCR-effectiveness” in five groups on the basis of their decrease in GCR intensity in percent, $\Delta I$ (%) using Kiel neutron monitor data, i.e. quiet ($\Delta I \approx 0.0$), small ($\Delta I \approx -0.01$ to $-0.49$ %); moderate ($\Delta I \approx -0.50$ to $-1.49$ %); large ($\Delta I \approx -1.50$ to $-2.99$ %); and very large ($\Delta I$ larger than $-3.00$ %) depression groups. Such a wide range in GCR effectiveness of ICMEs motivated us to look for the distinctions, if any, in the properties of average interplanetary plasma and field behavior during the passage of ICMEs responsible for the depressions of different range (small, moderate, large, and very large). We utilize GCR intensity data recorded by neutron monitors and solar-wind plasma/field data during the passage of ICMEs with different features and structures, and perform a superposed-epoch analysis of the data. We also adopt the best-fit approach with suitable functions to interpret the observed similarities and differences in various parameters. Using the GCR-effectiveness as a measure of cosmic-ray response to the passage of ICMEs, about half of the ICMEs identified during 1996 – 2009 are found to produce moderate to very large intensity depressions in GCR intensity. ICMEs associated with shocks/BDEs/MCs/halo-CMEs are more GCR-effective than ICMEs not associated with these structures/features. Each group (BDE/MC/halo) was subdivided into shock/no shock cases. A large difference in their GCR-effectiveness is observed; shock/sheath associated BDE/MC/halo ICMEs are much more GCR-effective than those not associated with any shock/sheath region. This difference is most prominent in case of shock/sheath associated ICMEs rather than those not associated with shock/sheath region. This emphasizes the role of the shock/sheath region in producing larger depressions in GCR intensity. Further, the characteristic recovery time of GCR intensity due to shock/BDE/MC/halo-CME-associated ICMEs is larger than those due to ICMEs not associated with these structures/features. This work has been published in Solar Physics in 2014.

As mentioned earlier ICMEs and CIRs are the two main large-scale structures in the heliosphere. Heliosphere is the region of space around the Sun in which the solar wind dominates. Next we compare the cosmic-ray response of ICMEs and CIRs
during their passage in near-Earth space. We study the relative importance of various structures/features identified during the passage of ICMEs and CIRs observed during solar cycle 23 (1995 – 2009). As the plasma and field properties are different during the passage of different structures, both in ICMEs and CIRs, we systematically vary epoch time in our superposed-epoch analysis one by one. In this way, we study the role and effects of each identified individual structures/features during the passage of ICMEs and CIRs. The average amplitude of GCR intensity depression for ICMEs is ~1.5 % as compared for CIRs which is ~ 0.5 %. The ratio of GCR depressions for ICMEs with shock to ICMEs without shock is ~2.5, and the ratio of intensity depression due to shock-associated CIRs to non-shock CIRs is also nearly the same. From the average plots obtained from superposed-epoch analysis, the time variation of GCR intensity due to ICMEs, during the main (decrease) phase, is found to be better correlated with time variation of magnetic field vector. However time variation of solar-wind velocity better correlates with GCR intensity during this phase, in case of decrease due to CIRs. The temporal variation of GCR intensity is found to be better correlated with simultaneous variations in solar-wind velocity, during the recovery of decrease (recovery phase) both due to ICMEs as well CIRs. This work has been submitted for publication in Solar Physics.

The continuous flow of the ambient solar wind is often overlaid by faster streams, as is evident from observations of the solar plasma in space. These so called high-speed solar-wind streams (HSS) are recognized as those ejected from solar active regions during coronal mass ejections (CMEs) and those coming from diverging and unipolar-field regions called coronal holes (CH). As a consequence, there are two classes of interplanetary structures related to two types of magnetic-field topology on the Sun, i.e. interplanetary coronal mass ejections (ICMEs) and corotating interaction region (CIRs). Both the ICMEs and the CIRs are capable of driving shocks in the interplanetary space due to interaction between high-speed CME/CH-streams and ambient solar wind. These HSS, as observed in near-Earth space, may be associated to different solar sources, e.g. i) a coronal hole, ii) a CME, iii) multiple coronal holes, iv) multiple CMEs, or v) compound streams due to coronal hole(s) and CME(s). The streams of i) different speed, ii) different duration, and iii) associated with different solar/interplanetary structures are likely to exhibit different responses in cosmic-ray intensity variations, both in amplitude and time profile. So we have also studied the
modulation of galactic cosmic rays (GCR) due to high-speed streams (HSS) identified in the solar wind. We compare the GCR modulation due to i) streams with different speed, ii) streams of different duration, and iii) streams from different solar sources. We also investigate the solar sources, interplanetary causes, and physical mechanisms responsible for GCR-intensity decreases of different amplitude, duration, and time profile, such as the so-called Forbush decreases, corotating decreases, long-lived, and multiple-dip cosmic-ray decreases.

On the average, GCR-intensity decreases at the arrival of the stream. HSS of higher speed and/or higher duration produce more depressions in GCR intensity. Multiple CME streams are found to be most, and single CH streams are least effective in modulating the GCR intensity. The rate of intensity decrease with increase in solar-wind velocity during the decreasing phase is highest for multiple CME streams and lowest for single CH streams. We observe that the intensity depression is strongest when the shock occurred both at the start of the HSS and in between the start and the end of the HSS. *This work has been published in Solar Physics in 2014.*