The subject of cosmic rays (CR) in interplanetary space brings together several areas of active research like solar wind, space weather, structure of the interplanetary magnetic field (IMF), variation of cosmic ray intensity (CRI) over long and short time scales, the propagation of solar cosmic rays in heliosphere and it’s modulation etc (see reviews: Lockwood, 1971; Rao, 1972; Storini, 1990; Venkatesan and Badruddin, 1990; Potgieter, 1994; Cane, 2000; Duldig, 2001; Kudela et al., 2000; Kudela, 2007). All this started with the historic 1912 balloon ascent by Victor Hess carrying equipments which established with certainty the extra-terrestrial nature of CR. Soon it became clear that CR were not electromagnetic radiation but consisted of electrically charged particles; the primaries impinging on the top of the atmosphere were clearly identified as atomic nuclei of
elements. Protons were the most abundant, followed by alpha particles, roughly in the ratio $10:1$, which reflects the same relative abundance observed throughout the universe. On the other hand, heavier nuclei, although relatively scarce ($\sim 1$), were also present. Some small amounts of electrons ($\sim 0.1-0.5\%$) also exist.

So one can say that CR are energetic particles which are found in the space and filter through our atmosphere. They come from all directions in space and their exact origin is unknown, though it is certainly outside the heliosphere. CRI is being regularly monitored by ground–based neutron monitors at several locations on the earth for the last several decades. These ground based neutron monitors respond to approximately $500$ MeV – $20$ GeV portion of the primary CR spectrum. The portion of the CR spectrum that reaches the earth’s atmosphere is controlled by the geomagnetic cut–off, which varies from a minimum (theoretically zero) at the magnetic poles to a vertical CR cut–off of about $15$ GV (ranging from $13$ GV to $17$ GV) in the equatorial region. Observations so far indicate a clear solar cycle effect with largest reductions in CR neutron monitor intensity during sunspot maximum years, a very good anti–correlation (long term variation) (Forbush, 1954; Ahluwalia and Wilson, 1996; and references therein). This approximately 11–year variation, anticorrelated with solar activity, with perhaps some time lag, is a fact that was firstly studied by Forbush (1958) and by many subsequent researchers (e.g., Pomerantz and Duggal, 1974; Perko and Fisk, 1983). Many research groups have tried to express this long–term variation of the CRI through means of appropriate solar indices and geophysical parameters (see chapter 2 for details), such as the sunspot number (Nagashima and Morishita, 1980), solar flares (Hatton, 1980), and the geomagnetic index (Chirkov and Kuzmin, 1979). Burlaga et al. (1985) proposed that fast coronal mass ejections
(CMEs) contribute to form a propagating diffusion region (heliocentric barrier) further out in the heliosphere, and CRI never quite recovers at the earth’s orbit (Burlaga et al., 1993). Kota and Jokipii (1983) envisaged the dependence of the CR modulation on the orientation of the solar magnetic dipole moment also so that a complete modulation would involve two solar cycles (Hale magnetic cycle of ~ 22 years) (Hale and Nicholson, 1925). These long term variations and models/theories on these variations are discussed later in this chapter. The spectra of galactic CR are modulated by the sun (and its magnetic field) because the charged particles must fight their ways inward against the rapidly expanding solar wind (Kane, 2003).

The modulation of the galactic CR in the heliosphere using theoretical as well as empirical approaches is successful and has advanced rapidly (Potgieter, 1998). However, an adequate description of the effect of the heliosphere on CR still does not appear to be a simple task. To be adequate, theoretical models should consider the complex shape and dynamics of heliospheric current sheet (HCS), the heliolatitudinal distribution of the solar wind velocity, boundaries between fast and slow solar wind streams, various sporadic and recurrent structures, and the role of the termination shock and the heliopause. So, it is extremely difficult to deduce the global mechanisms that produce this long-term modulation even although we have continuous observations at 1 AU of CR spectra and intensity as a function of time and solar activity. The last few decades have seen major advances in our understanding of CR modulation. The Ulysses mission made two cut-of-ecliptic orbits around the sun and revealed the three dimensional structure of the solar wind, magnetic fields and CR in the heliosphere. Pioneer and Voyager missions revealed the vast dimensions of the outer heliosphere.
1.1 Heliosphere

Heliosphere is the region of space where the solar wind's momentum is sufficiently high that it excludes the interstellar medium. The solar wind plasma thus dominates this region (see Figures 1.1 and 1.2).

Actually, heliosphere extends from the solar corona to an outer boundary where the solar wind encounters the interstellar medium (Parker, 1958). The outer corona of the sun consists of a fully ionized gas threaded by magnetic fields rooted in the visible surface of the sun, the photosphere. The coronal plasma is very hot, with a temperature in excess of a million degrees. It is still unclear just how the corona is heated to such temperatures; the most likely explanation is that waves from the lower layers of the solar atmosphere provide the necessary energy to heat the corona. The energy deposited in the coronal plasma appears also to be sufficient to accelerate it away from the sun in the form of the solar wind. The speed of the solar wind varies from about 300 km/s to more than 800 km/s. This speed is well in excess of the speed of sound in the plasma.

This solar wind streaming outwards from the sun is made up of particles, mainly protons, electrons and alpha particles (helium nuclei); these are typically boiled off from the solar corona. Solar gravity is unable to retain the material and thus a continuous solar wind results. The density decreases with increasing distance from the sun, eventually becoming a low density wind of outward moving particles. The solar wind density near the earth (1 AU) is generally around 5–10 particles per cubic centimeter. On occasions it could reach values of 800–1000 atoms per cubic centimeter; these occur when solar flares and other disturbances take place in the solar atmosphere (Venkatesan and Badruddin, 1990).
Figure 1.1: Artistic view of the heliosphere
Figure 1.2: Schematic diagram of the heliosphere
Although the solar wind moves out almost radially from the sun, the rotation of the sun gives the magnetic field the form of a three-dimensional Archimedean spiral, known as the Parker spiral (Parker, 1963) (see Figure 1.3). Sun does not rotate rigidly but differentially, with the solar poles rotating ~ 20% slower than the solar equator. The interplay between the differential rotation of the magnetic field line footprints in the photosphere and the subsequent non-radial expansion of the solar wind from the coronal holes results in magnetic field excursions in heliographic latitude. The direction (polarity) of the field in the sun’s northern hemisphere is opposite to that of the field in the southern hemisphere, and reverses at solar maximum. The shape of the IMF depends on the sun’s 11-year cycle of magnetic activity. Near activity minimum, the large-scale global magnetism of the sun can be described as a single magnet with north and south poles. The northern pole is of one magnetic polarity or direction, and the southern pole is of opposite polarity. The negative and positive field lines meet near the solar equator where a magnetically neutral layer, called heliospheric current sheet (is discussed later in this chapter), is dragged out into space by outflowing wind. The dipole is stretched way out at its middle, resulting into two polar monopoles whose magnetic field lines do not cross the equatorial region. This magnetic orientation is preserved throughout most of an 11-year activity cycle. The polarity of the sun’s magnetic field reverses during solar activity maximum (i.e., the magnetic field that is pointed toward the sun is directed away during the next cycle, and vice versa, returning back to the original direction every 22-years). The approximately 11-year solar activity cycle is reflected in the strength of the IMF, the frequency of CMEs and shocks propagating outward, and the strength of those shocks. The solar magnetic field reverses at each solar activity maximum, resulting in
Figure 1.3: A schematic drawing of the pattern of the mean magnetic field in the heliosphere
22-year cycles as well. The field orientation is known as its polarity and is positive when the field is outward from the sun in the northern hemisphere (e.g. during the 1970s and 1990s) and negative when the field is outward in the southern hemisphere (e.g. during the 1960s, and 1980s). A positive polarity field is denoted by \( A > 0 \) epoch and a negative field by \( A < 0 \) epoch (Duldig, 2001).

The question of the size of the heliosphere is intimately related to the question of the position and nature of the heliopause and an associated internal shock that arises to slow the solar wind flow before it collides with the interstellar flow. The existence of a standing shock prior to the heliopause was proposed around five decades ago (Parker, 1961). On the upwind side after crossing the shock, the streamlines curve away from the original radial direction. The geometry is essentially caused by the nose–to–tail pressure gradient arising due to the motion of the heliosphere though the interstellar medium. The region between the terminal shock and the heliopause is called the heliosheath. In the direction opposite to the upwind direction the solar wind flows in the same direction as the interstellar flow, down what is know as the “heliotail”. At the heliopause, which divides the solar wind plasma from the interstellar plasma, magnetic field reconnection may occur (Venkatesan and Badruddin, 1990). The heliopause thus confines the solar wind within a magnetic bubble and gives rise to the name, heliomagnetosphere or heliosphere for short. Within the region of shock front the magnetic field is along the so called Archimedean spiral, while the plasma outflow is radial; outside the shock front, the magnetic fields are disordered and the plasma flow is visualized as turbulent.

Beyond the heliopause is the outer stellar wind; the interstellar medium contains fields and particles unaffected by the solar plasma. The motion of the solar system in the interstellar medium is believed
to generate a bow shock. Currently we do not know where the heliopause is; but we guess it at ~ 150 AU from the sun in the direction the solar system is traveling. Locating the heliopause and finding out the nature of the interstellar medium beyond the heliopause is an important guess. Outside the heliopause one expects to find the stellar wind flow.

As of May 9, 2008, Voyager 1 is about 106.26 AU (16 billion km) from the sun, and has thus entered the heliosheath, the termination shock region between the solar system and interstellar space, a vast area where the sun's influence gives way to the other bodies in the galaxy. As mentioned above, the termination shock region, a part of which is the heliosheath, is the area of local space in which Voyager 1 is currently passing through, with the current goal of reaching and studying the heliopause, which is the known boundary of our stellar system (Wikipedia website).

1.2 Heliospheric current sheet

The outward expansion of the solar wind, combined with the rotation of the sun, gives rise to two important physical phenomena. First, the solar plasma tends to be confined to a sheet like region around the solar equator forming a "plasma sheet" in the heliosphere, somewhat analogous to the plasma sheet in the earth's magnetotail. Second, because the solar magnetic field is embedded in the radially outward flowing solar plasma, yet tied firmly to the sun at the solar photosphere, the field in the interplanetary space forms a spiral pattern, similar to that produced by a rotating garden water sprinkler. The heliosphere plasma sheet (also known as heliospheric neutral sheet or heliospheric current sheet (HCS)), is not rigid but
rather assumes a warped, fairly wavy pattern in interplanetary space, so that at any given time the earth or any other planet can be above, below or within the plasma sheet (see Figures 1.4 and 1.5). At the orbit of the earth, the IMF makes an average angle to the radial direction of ~ 45°; at the orbit of Jupiter the interplanetary field is nearly perpendicular to the sun–planet line (Venkatesan and Badruddin, 1990).

The HCS separates the two oppositely directed magnetic polarity hemispheres of the heliosphere (Smith et al., 1978; Jokipii and Thomas, 1981). The angle between the mean plane of the current sheet and a plane that is an extension of the sun’s equator is referred to as the tilt angle (TA) or inclination (α) of the current sheet or pseudoinclination of the HCS. In practice, α is obtained from the computed coronal magnetic field maps of the Wilcox Solar Observatory (WSO) at Stanford University (Hoeksema, 1989, 1992) by averaging the maximum latitudinal excursions (north and south) of the coronal neutral line during each Carrington rotation. Near sunspot minimum these two planes nearly coincide, and the angle α is close to 0°.

TA shows a variation with solar activity and hence exhibits a periodicity of ~ 11 years (periodicity of a solar cycle). The tilt increases as the solar cycle progresses until it is quite large near solar maximum at which time the polarity of the sun’s dipolar magnetic field reverses. The tilt of the current sheet then gradually decreases again to a value close to 0° at the next minimum in solar activity.

An inclined current sheet has a significant effect on the global heliospheric field and on the drift motions of the CR particles. These implications were pointed out by Jokipii, who proceeded to include drift effects in the basic transport equation (see section 1.4) used to describe the behavior of energetic particles (Jokipii et al., 1977).
Figure 1.4: Artistic view of the heliospheric current sheet
Figure 1.5: Schematic diagram of the heliospheric current sheet
In particular, the HCS was shown to cause fast drifts along it and to act as a major source or sink of CR in the heliosphere (depending on the polarity of the fields above and below it, which change sign from one sunspot cycle to the next). The influence of the HCS was evident in the model as a correlation between CRI and the changing inclination of the current sheet. This aspect of the model was shown to be consistent with observations (Smith, 1990). Saito and Swinson (1985, 1986) compared neutron monitor data from Mount Washington from 1971 to 1974 with the tilt of current sheet, determined from k–corona data; they found that there was a general inverse correlation between the CRI at the earth and the tilt of the neutral sheet over that four years period. Smith and Thomas (1986) performed a similar analysis, comparing the maximum latitudinal extent of the current sheet into the northern and southern solar hemispheres with CR data from the Deep River neutron monitor and from Pioneer 10 for the years 1976 to 1982. Again they found an inverse relation between tilt of the current sheet and CRI. They found that the inverse relation was more pronounced after the reversal of the sun’s magnetic field in 1979–1981 (when the magnetic phase became negative) than before the reversal (when the magnetic phase was positive); however these conclusions were based upon only a few years of data in each sample. In an analysis comparing Mount Washington neutron monitor data from 1984 to 1987 with the tilt of the current sheet, Webber and Lockwood (1988) confirmed the inverse relation between these two parameters during these years (see chapter 3 for details).

Other importance of the HCS is its close relation with plasma parameters. Since the HCS serves as a magnetic equator, many solar wind properties are organized with respect to it. Studies of various plasma parameters, including solar wind speed, density, temperature,
and composition, show a close correlation with the current sheet (see Smith, 2001 and references therein).

1.3 Solar modulation of galactic cosmic rays: Basic concepts

The CR transport in a magnetic field which is a function of position and time, and which is frozen into the outward-moving plasma is briefly discussed here. Physics of this phenomenon in terms of the transport of the energetic particles in the plasma flow and magnetic field configuration of the heliosphere is reviewed by Jokipii (1989). The CR particles are subjected to four distinct transport effects which contribute to two distinct kinds of motion. There is a general guiding center motion which occurs at the same time as a random walk or spatial diffusion. More specifically, since the particles tend to stay on a given field line, they are convected with the fluid flow. The magnetic field varies systematically over large scales, so there are, in addition, curvature and gradient drifts which are coherent over large distances. Because of the $\mathbf{v} \times \mathbf{B}$ electric field of the wind, there are associated energy changes. The random walk or spatial diffusion is caused by the scattering by random magnetic irregularities.

The resulting transport is a superposition of these coherent and random effects. They were combined first by Parker (1965), to obtain the generally accepted transport equation for the quasi-isotropic distribution function $f(\vec{r}, p, t)$ of CR of momentum $p$ at positions $\vec{r}$ and time $t$. 
\[ \frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i} \left[ \kappa_n \frac{\partial f}{\partial x_j} \right] \]  
(diffusion)

\[-U_i \frac{\partial f}{\partial x_i}\]  
(convection)

\[-V_{di} \frac{\partial f}{\partial x_i}\]  
(gradient - center drift)

\[+ \frac{1}{3} \frac{\partial U_i}{\partial x_i} \left( \frac{\partial f}{\partial \ln p} \right)\]  
(energy change)

\[+ Q(x_i, t, p)\]  
(source)  \( (1.1) \)

The labels next to each of the various terms indicate the associated physical effect. The guiding center drift velocity is given in terms of the local magnetic field \( \vec{B} \) and the particle charge \( q \) by

\[ \vec{V}_d = \left( pcw/3q \right) \nabla \times \left( \vec{B} / B^2 \right) \]

This transport equation is remarkably general, and has been used in most discussions of CR transport and acceleration. Modulation theory consists of the application of equation (1.1) to galactic CR in the heliosphere. The source \( Q \) is set equal to zero, and an external boundary condition reflecting the external bath of galactic CR is imposed (Jokipii, 1989).
It is generally accepted (see McDonald et al., 1993; Potgieter, 1994) that all of the above processes are important, but that their relative importance varies throughout the solar cycle. In the period near the solar minimum, when the magnetic structure of the heliosphere is particularly simple and approximates the ideal of two hemispheres of opposite magnetic polarity separated by an equatorial current sheet, drifts may play an important role in the transport of CR through the heliosphere. And thus the wavy HCS has turned out to be one of the most successful physical effects in CR modulation modeling (Jokipii et al., 1977). The tilt of the HCS has become a prime indicator of solar activity from a drift point of view, and is widely used in data interpretation and modeling (Hoeksema, 1992). Even here, though, Jokipii and Kota (1989) pointed out that irregularities in the polar fields may become important enough at large radii to significantly diminish the effectiveness of drifts. In the complex magnetic structure characteristics of solar maximum, it is likely that drifts play only a small role and that modulation is dominated by large scale disturbances in the solar wind (McKibben et al., 1995).

The diffusion and convection component of equation (1.1) are independent of the solar polarity and will only vary with the solar activity cycle. Conversely, the drift components will have opposite effects in each activity cycle following the field reversal. Jokipii et al. (1977) and Isenberg and Jokipii (1978) investigated the effects of this polarity dependence by numerically solving the transport equation. They showed that the CR would essentially enter the heliosphere along the helio-equator and exit via the poles in the A < 0 polarity state. In the A > 0 polarity state the flow would be reversed, with particles entering over the poles and exiting along the equator (see Figure 1.6). Kota (1979) and Jokipii and Thomas (1981) showed that the current sheet would play a more prominent role in the A < 0 state.
Figure 1.6: Cosmic ray drift patterns during two polarity epochs
when CR enter the heliosphere along the helio-equator and would interact with the sheet. Because the particles enter over the poles in the $A > 0$ state, they rarely encounter the current sheet on their inward journey, and the density is thus relatively unaffected by the current sheet in this state. It was clear from the models that there would be a radial gradient in the CR density, and that the gradient would vary with solar activity. Thus the CR density would exhibit the 11-year solar cycle variation, with minimum CR density at times of solar maximum activity (and field reversal) (Duldig, 2001).

Once it was realized that gradient and curvature drifts should play an important role in modulation, Jokipii and Thomas (1981) and Kota and Jokipii (1983) identified the inclination $\alpha$ of the HCS as a key parameter for models of galactic CR modulation. As discussed earlier in section 1.2 of this chapter, correlations between the TA and the CRI have been obtained by Smith and Thomas (1986), Webber and Lockwood (1988), and Smith (1990). In accord with drift theory, the slope of these correlations depends on the polarity of the cycle, with CRI being less sensitive to changes in TA during a positive cycle (Fluckiger, 1991). The predictions by drift models of different shapes of galactic CRI maxima in two consecutive cycles are based on the assumption that the evolution of the HCS does not vary greatly from cycle to cycle. This assumption makes it possible to attribute the differences in the shapes of successive CR maxima to the different directions of particle entry during $A > 0$ and $A < 0$ cycle. Particles entering the heliosphere from the directions of the poles during the minima of $A > 0$ epochs are relatively unaffected by changes in TA, leading to broad galactic CR maxima. During $A < 0$ epochs, particles entering along the HCS sense structural changes, indicated by the variation of TA, more rapidly, leading to more peaked (or triangular) galactic CR maxima (Cliver, 1993).
1.4 Relations, lag and hysteresis between solar activity and cosmic rays

Galactic CR in the energy range from several hundreds MeV to tens of GeV are subjected to heliospheric modulation, under the influence of solar output and its variation. The heliospheric modulation of CRI and spectrum are associated with the 11-year solar activity cycle. The charge/polarity dependence of the drift mechanism is clearly observed in CR modulation in terms of 22-year solar magnetic cycle, showing different shapes of CR maxima in alternate solar cycles. Long-term CR modulation in the high energy range is studied using the global network of CR neutron monitoring stations having different geomagnetic cut-off rigidities. Neutron monitors are most sensitive to CR in the energy range 0.5–20 GeV, which coincides with the maximum energy response for an effective solar modulation. Though, the anti-correlation between solar activity and galactic CR reaching the earth is a well established fact (see Figure 1.7), however, the degree of anti-correlation is found to vary during different phases of solar cycles (Dorman and Dorman, 1967; Pomerantz and Duggal, 1971; Rao, 1972; Nagashima and Morishita, 1979; Mavromichalaki and Petropoulos, 1984; Webber and Lockwood, 1988; Nymmik and Suslow, 1995; Storini, et al., 1995; Ahluwalia and Wilson, 1996; Dorman et al., 2001b; Usoskin et al., 2002). Although the modulation of CR has been studied for several decades, it is still a subject of intense research to asses the continuously changing behavior of the sun and its influence on CR. Diffusive/drift propagation of CR particles along with heliospheric disturbances in the large-scale heliosphere causes a time lag between solar activity and CRI. The time lag between CRI and solar activity as well as the amplitude of
the modulation varies from cycle to cycle (Dorman and Dorman, 1967; Nagashima and Morishita, 1979; Mavromichalaki et al., 1990; Van Allen, 2000, Mishra et al., 2006).

The variations in the CRI are on several time scales. Forbush decreases occur in matter of days (Forbush, 1938; Lockwood, 1971; Badruddin et al., 1986, 1991; Venkatesan et al., 1992; Badruddin, 2000, 2002, 2006; Kudela and Brenkus, 2004; Singh and Badruddin, 2006). Then, there are 27–day variations (e.g. Venkatesan et al., 1982; Richardson et al., 1996; Badruddin, 1997; Singh and Badruddin, 2007). On the longer time scale, there is a year to year variation almost anti-parallel to the 11-year sunspot cycle (Forbush, 1958; Pomerantz and Duggal, 1974; Perko and Fisk, 1983, and references therein), but with differences in the even and odd cycles (22-year modulation) (see Figure 1.7). The CR modulation starts with a delay with respect to sunspots and the delay is different in odd cycles (e.g. 19, 21) and even cycles (e.g. 20, 22).

A great effort is carried out in order to express this long-term variation of galactic CR intensity by appropriate solar indices. It is already mentioned that sunspot number has been used by Nagashima and Morishita, (1980), solar flares by Hatton (1980) and geomagnetic index by Chirkov and Kuzmin (1979). Other authors like Xanthakis, Mavromichalaki, and Petropoulos (1981) and Nagashima and Morishita, (1980) have taken into account the contribution of more than one solar and/or geophysical parameters to the modulation process. Mavromichalaki and Petropoulos (1984) found a relation between the modulated CRI during the 20th solar cycle, and a combination of the relative sunspot number, the number of proton events and the geomagnetic index Ap. In a later work, Mavromichalaki and Petropoulos (1987) improved this empirical relation by including the number of corotating solar wind streams.
**Figure 1.7:** Anti correlation between sunspot number and cosmic ray intensity (Climax NM). Numbers in boxes show solar cycles. Polarity reversal periods are shown by grey colored dashed bars.
On the other hand Lockwood and Webber (1984) found a close relationship between the magnitude and frequency of Forbush decreases and the 11-year cosmic ray variation; they conclude that the effect of Forbush and other transient decreases are the dominant factors in the long-term intensity modulation.

In addition to the solar cycle variation, CR fluxes exhibit a 22-year cycle variation also, which is associated with solar magnetic cycle. The CRI show a plateau of maximum flux level centered about the solar minima of A > 0 solar cycles while during A < 0 solar cycles the fluxes peak sharply at the solar minima (see Figure 1.7). The behavior is a prediction of the drift model (Kota and Jokipii, 1983), indicating that CR modulation at solar minima is dominated by drift transport mechanism. The reason for this behavior is that during A > 0 cycle, as explained earlier, particles drift in from the poles and only when the tilt of the current sheet gets very large (close to 90°) the particle drift path is affected; however, during A < 0 cycles, particles drift is along the current sheet and their paths sensitively depend on the TA. The 22-year magnetic cycle variation also shows up in cosmic ray electron to proton flux ratio e/p (Evenson, 1998; Heber and Marsden, 2001; Heber et al., 2002), the e/p ratio during the A < 0 solar cycle is greater than during the A < 0 cycle, because electrons drift more easily from polar regions in the A > 0 cycle while protons do the same in the A > 0 cycle (Zang, 2003).

The mechanism for CR modulation consist of time dependent heliospheric drifts and outward propagating diffusive barriers, which are formed by merging of CMEs, shocks and high speed flows at 10–15 AU from the sun (Merged Interaction Regions, MIRs; Burlaga et al., 1985). Since only some MIRs are effective in modulating CR throughout the heliosphere (Burlaga et al., 1993), global MIR (GMIR) were conceived which are regions extending 360° around the sun mostly in
the ecliptic plane and responsible for the step-like changes in CR counting rates. The convection diffusion mechanism is independent of the sign of the solar magnetic field and operates similarly in every 11-year sunspot cycle (Dorman, 1959; Parker, 1963, and others). On the other hand, the drift mechanism gives opposite effects with the changing sign of solar magnetic field in alternate cycles (Jokipii and Davila, 1981; Jokipii and Thomas, 1981; Lee and Fisk, 1981; Potgieter and Moraal, 1985, and many other further papers). At the sunspot maximum of odd cycles, the solar north-polar magnetic field reverses, from outward directed ($A > 0$) to inward directed ($A < 0$) during an interval of a few months. A few months later, the solar south-polar magnetic field also reverses, from inward directed ($A < 0$) to outward directed ($A > 0$) during an interval of few months. In even cycles, the opposite occurs. In $A > 0$ epochs, the inflows of CR into the inner heliosphere are faster from over the poles than from along the heliospheric current. When $A < 0$, the opposite occurs (Wibberenz et al., 2002). Cane et al. (1999) have reported a very good anti-correlation between CR changes and interplanetary total magnetic field for two consecutive cycles 21 and 22, and a very close relationship between CR and TA of the wavy current sheet in the heliosphere, which has been claimed to be very successful as a proxy for solar activity in CR modulation models with particle drift included. It may be noted that the HCS tilt angle is considered to be a good proxy of solar activity in even cycles during low to moderate modulation conditions (tilt angle below $35^\circ$-$40^\circ$), while for higher solar activity and for odd cycles, the tilt angle dependents is not so clear (Kane, 2007).

The CR modulation depth observed at the earth is a result of the combined action of solar and heliospheric conditions that control the CR behavior all over the heliomagnetosphere. The delay of the CR
effects relative to processes in the sun (hysteresis of CR) has been known since long ago (Belov et al., 2006 and references therein). The investigation of the hysteresis phenomenon between long-term variations in CRI, observed at the earth, and solar activity started many years ago (Dorman, 1957; Neher and Anderson, 1962). The same hysteresis is also observed when comparing particle fluxes of different energies (Van Hollebeke et al., 1973; Garcia-Munoz et al., 1973; Ozguc and Atac, 2003). Here CR maxima (minima) do not seem to coincide exactly with the solar activity minima (maxima). There is often a lag of a few months, detected more than 50 years ago (e.g., Dorman, 1957; Neher and Anderson, 1962, and later, many others). The lag has been used to estimate the radius of CR modulation region. Earlier estimates, based on comparison with coronal green line or by examining CR modulation caused by sudden jumps in solar activity (Dorman et al., 2001a, and references therein) indicated that the radius was very small, about 5AU, not more than 10–15 AU. Dorman (1975, and references therein) initiated the use of a convection-diffusion model, taking into account the time lag of processes in the interplanetary space relative to the processes on the sun and concluded that the modulation region should be much larger, between 50 and 150 AU. Further, Dorman (2001) took into account the drift effects (as depending upon the sign of solar polar magnetic field) according to Burger and Potgieter (1999) and showed different effects for even and odd solar cycles (see also Dorman et al., 2001a, 2001b; Kane, 2003).

Even today, the knowledge about these time lags or hysteresis is still fragmentary and even contradictory. Comparing the particle flux lags during even and odd cycles, some researchers (see, for example Badhwar and O’Neill, 1993) indicated no lag, where as others (Lopate
and Simpson, 1991) claimed a smaller lag (1–2 months) during even cycles compared with odd cycles (9–11 months).

The survey presented above shows that the whole area of long-term (~ 11 and 22 year) modulation, time lag and hysteresis effects observed in modulations, their dependence on solar activity and solar polarity is interesting and complex; and needs their detailed study using as many solar/interplanetary parameters as possible, extended over long period during different solar and magnetic conditions. It is hoped that a systematic and detailed approach to these aspects will help in not only understanding various observed phenomena but also to understand the modulation process more clearly and thoroughly.

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