SOLAR AND HELIOSPHERIC MODULATION OF GALACTIC COSMIC RAYS

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(Received 10 September 2005; Accepted in final form 6 March 2006)

Abstract. The significance of external influences on the environment of Earth and its atmosphere has become evident during recent years. Especially, on time scales of several hundred years, the cosmogenic isotope concentration during the Wolf-, Spoerer-, Maunder- and Dalton-Minimum indicates an increased cosmic ray flux. Because these grand minima of solar activity coincide with cold periods, a correlation of the Earth climate with the cosmic ray intensities is plausible. Any quantitative study of the effects of energetic particles on the atmosphere and environment of the Earth must address their transport to Earth and their interactions with the Earth's atmosphere including their filtering by the terrestrial magnetosphere. The first problem is one of the fundamental problems in modern cosmic ray astrophysics, and corresponding studies began in the 1960s based on Parker's cosmic ray modulation theory taking into account diffusion, convection, adiabatic deceleration, and (later) the drift of energetic particles in the global heliospheric magnetic field. It is well established that all of these processes determining the modulation of cosmic rays are depending on parameters that are varying with the solar magnetic cycle. Therefore, the galactic cosmic ray intensities close to Earth is the result of a complex modulation of the interstellar galactic spectrum within the heliosphere. The modern view of this cosmic ray modulation is summarized in our contribution.

Keywords: cosmic rays, solar activity, modulation, heliosphere, particle transport in astrophysical plasmas, solar terrestrial relation

1. Introduction

Victor Hess discovered in 1912 an evidence of a very penetrating radiation (cosmic rays) coming from outside our atmosphere, which is dominated by hydrogen and helium (Simpson, 1983). At energies below a few GeV per nucleon the influence of solar and heliospheric modulation on the galactic cosmic ray energy spectra becomes important. Figure 1 shows in panel (A) the monthly averaged count rates of cosmic rays measured at 1 AU by the Kiel neutron monitor and in panel (B) the monthly sunspot number (black line) and the evolution of the maximum latitudinal extension of the heliospheric current sheet (tilt angle, red line). From the Figure two characteristics of the cosmic ray intensity history are evident:

Space Science Reviews (2006) 125: 81–93
DOI: 10.1007/s11214-006-9048-3

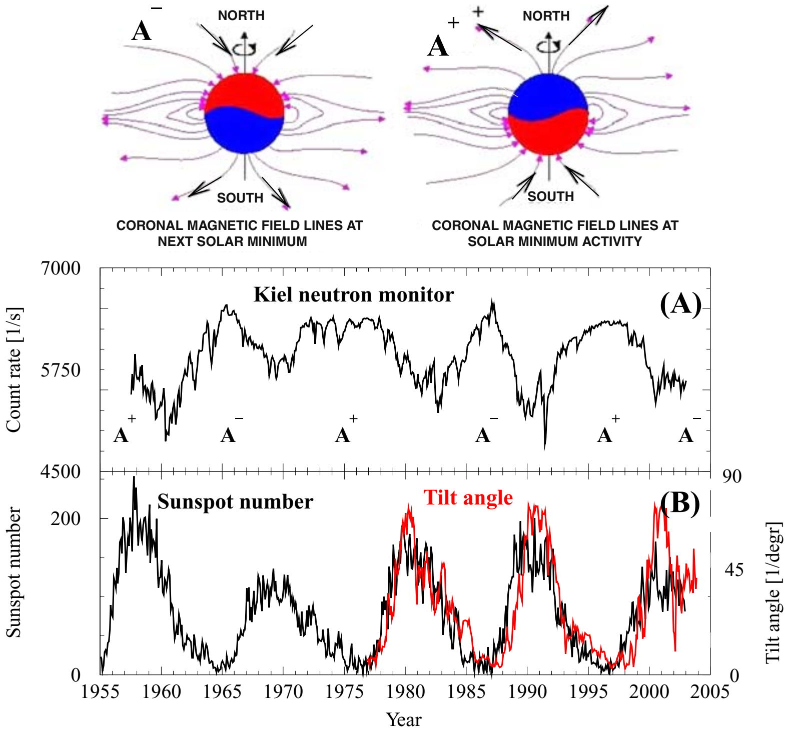

Figure 1. Solar modulation of galactic cosmic rays, monthly sunspot number and tilt angle α of the heliospheric current sheet. Marked by A^+ (A^-) are times when the solar magnetic field is directed inward (outward) from the Sun in the northern polar and outward (inward) in the southern polar region, as sketched on top (Scherer *et al.*, 2004).

1. The cosmic ray flux is varying in anti-correlation with the 11-year solar activity cycle, leading to the conclusion that galactic cosmic rays entering the regions close to the Sun are modulated as they traverse the region controlled by the Sun, called the heliosphere.
2. In the 1960s and 1980s, when the solar magnetic field is pointing towards the Sun in the northern hemisphere, the time profiles are peaked, whereas they are more or less flat in the 1970s and 1990s during the opposite solar magnetic epoch, showing a correlation with the 22-year solar magnetic cycle.

Parker (1958) introduced the concept of the supersonic expansion of the solar corona, the solar wind. Its existence was confirmed with Mariner 2 in 1962 (Snyder and Neugebauer, 1963). The solar wind is a hot, tenuous plasma surrounding the Sun, with characteristic temperatures and particle densities of about 10^6 K and 10^{14} m^{-3} in the corona. The interaction of the supersonic solar wind with the local interstellar medium leads to a transition from supersonic to subsonic speeds at the heliospheric termination shock, which has been observed by Voyager I at a distance of about 94 AU (Stone *et al.*, 2005; Decker *et al.*, 2005). As suggested by sophisticated models (Scherer and Ferreira, 2005), supported by radio observations (Gurnett *et al.*, 2003), the boundary layer between the local interstellar medium and the solar wind, called the heliopause, is at about 125 AU.

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 Archemedean spiral, known as the Parker spiral (Parker, 1963). Fisk (1996) pointed out that a different correction needs to be made to the Parker spiral model for the simple reason that the 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 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. A heliospheric current sheet separates the two polarities. This current sheet is tilted because of an offset between the Sun's rotational and magnetic axes. The tilt angle α is varying with the solar cycle from low ($<10^\circ$) to high ($>70^\circ$) values during solar maximum (Hoeksema, 1995).

2. Transport of Charged Particles in the Heliosphere

In order to understand the modulation of cosmic rays in the heliosphere it is vital to review the theory and observation of the particle transport in the heliosphere during periods of solar minimum. It is the variation of these transport parameters which causes the cosmic ray flux to vary with the solar cycle.

2.1. The Particle Transport Equation

The transport of cosmic rays in the heliosphere is described by Parker's (1965) transport equation, as discussed in detail by Potgieter (1998). Let $f(\mathbf{r}, P, t)$ be the differential cosmic ray distribution function, $\mathbf{r}$ the spatial coordinates, P the particle rigidity, and t the time:

$$\frac{\partial f}{\partial t} = -(\underbrace{\mathbf{V}}_{a} + \underbrace{\langle \mathbf{v}_D \rangle}_{d}) \cdot \nabla f + \underbrace{\nabla \cdot (\overleftrightarrow{\kappa} \cdot \nabla f)}_{c} + \underbrace{\frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{b} + \underbrace{Q}_{e} \qquad (1)$$

where terms on the right-hand side represent:

(a) Outward convection by the solar wind.
(b) Adiabatic deceleration from the divergence of the spherically expanding solar wind: In order to illustrate the effect of adiabatic deceleration Potgieter (1984) investigated the heliospheric propagation to Earth using series of "monoenergetic" local interstellar proton spectra. The results of this computation are shown

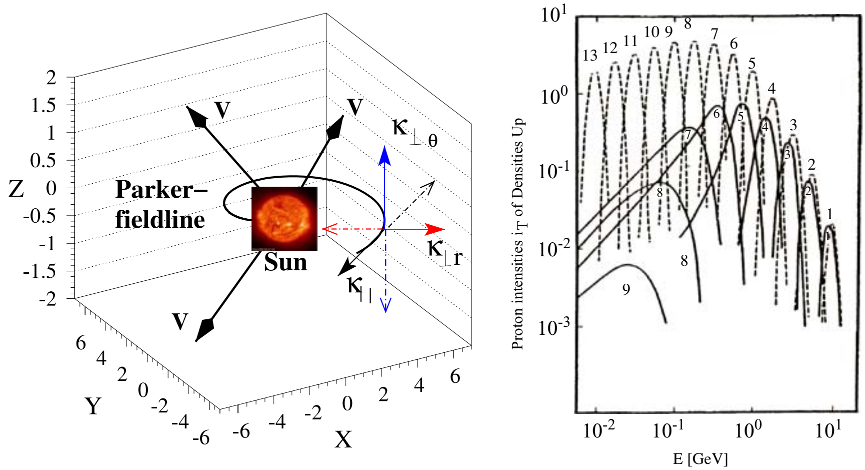

Figure 2. The different components of the diffusion tensor in the Parker-spiral (left). The arrows V indicate the expanding solar wind. On the right the effect of adiabatic deceleration on monoenergetic "interstellar" spectra is shown (for details see text, and Potgieter, 1984).

on the right side of Figure 2. It clearly illustrates the well-known E^1 power-law at low energies. The gaussian spectra numbered 8 to 13, the dotted lines in the right-hand panel of Figure 2, are spectra assumed in the local interstellar medium. The corresponding spectra at Earth are given by the solid lines 8 and 9. The contribution for lower energies (lines 10 to 13) are not shown because they contribute even less to the observations at Earth (see also Moraal, 1993).

(c) Diffusion ($\overleftrightarrow{\kappa}$) through the irregular heliospheric magnetic field in response to the gradient set up by convection and deceleration: $\overleftrightarrow{\kappa}$ consists of a parallel diffusion coefficient ($\kappa_{\|}$) and the perpendicular diffusion coefficient for the radial ($\kappa_{\perp r}$) and polar direction ($\kappa_{\perp \vartheta}$). Promising progress has been made in understanding the interaction of energetic particles with the solar wind and the calculation of the diffusion tensor in recent years (Parhi *et al.*, 2001; Bieber *et al.*, 2004; Shalchi and Schlickeiser, 2004, 2005). However, applying these diffusion tensors in modulation models are not able to explain Ulysses observations, discussed below.

(d) Gradient and curvature drifts ($\langle \mathbf{v}_D \rangle$) in the global heliospheric magnetic field (Jokipii *et al.*, 1977). In an A $>$ 0 solar epoch like in the 1970s and 1990s (c.f. Figure 1) with the solar magnetic field directed outward from the Sun in the northern polar region and inward in the southern polar region, positively charged particles are expected to drift into the inner heliosphere over the solar poles and out along the heliospheric current sheet. In the same phase of the solar cycle the drift pattern of negatively charged particles is reversed. The intensity of negatively charged particles is, therefore, expected to depend on the latitudinal excursion of the heliospheric current sheet in an A $>$ 0 cycle, whereas the intensity of positively charged particles should vary significantly less (Potgieter and le Roux, 1992). The situation reverses in an A < 0 magnetic cycle.

(e) Local sources like particles accelerated at the termination shock or interplanetary shocks.

2.2. Cosmic Ray Distribution at Recent Solar Minima

In order to understand solar and heliospheric modulation it is vital to reproduce the spatial distribution and the energy spectra of cosmic rays in the three-dimensional heliosphere around solar minimum periods. The second task is to investigate the solar cycle dependence of all propagation parameters. Keys to fulfill these tasks are to measure the cosmic ray distribution in the three-dimensional heliosphere and to model the cosmic ray transport in the heliospheric magnetic field in order to reproduce observations like the one shown in Figure 1. The combination of Ulysses, the Voyager, Pioneer and spacecraft at 1 AU constitute a unique network for studying the transport of galactic cosmic rays over a vast region of the heliosphere. The range of heliocentric distances and latitudes covered by Ulysses (U), Voyager (V1 and V2) and Pioneer 10 (P10) for the time period from mid 1993 to 2005 is shown in a semilog plot (Figure 3A).

Panel (B) of Figure 3 displays the cosmic ray spectra for protons for the 1965 and 1977 solar minimum, respectively. (1) It follows a E^1 law at several 10 MeV. From the Figure it is obvious that (2) the intensities are higher in the A > 0 than in the A < 0 solar magnetic epoch at energies below 700 MeV and (3) vice versa at energies above 700 MeV. (4) Due to the large gradients anomalous cosmic ray hydrogen can not be measured at Earth. However, Garcia-Munoz *et al.* (1973) found that the shape of the helium spectra does not follow the E^1 law during solar minimum. The current paradigm for the unexpected shape are anomalous cosmic rays (Fisk *et al.*, 1974). The principal ideas were further developed by Vasyliunas and Siscoe (1976), discussed in detail by Fichtner (2001). In connection with space climate it might be interesting to note that the anomalous cosmic ray helium flux is dominant at around 10 MeV per nucleon. The blue symbols in Figure 4C are the measured proton spectra at 63 AU. At energies below 100 MeV the observations are dominated by anomalous hydrogen, leading to the two peak structure.

While (1) and (4) are a consequence of the large energy losses in the heliosphere (2) and (3) can be attributed to the importance of drifts in the heliospheric magnetic field (Reinecke and Potgieter, 1994).

Another important prediction from drift-dominated modulation models is the expectation that protons will have large positive latitudinal gradients in an A > 0 solar magnetic epoch (Potgieter, 1998; Heber and Marsden, 2001). The dataset from the high heliospheric latitude ESA/NASA Ulysses mission is ideally suited to investigate galactic cosmic ray flux variations with heliospheric latitude (Marsden and Wenzel, 1981). Ulysses was launched towards Jupiter in October 1990 in the

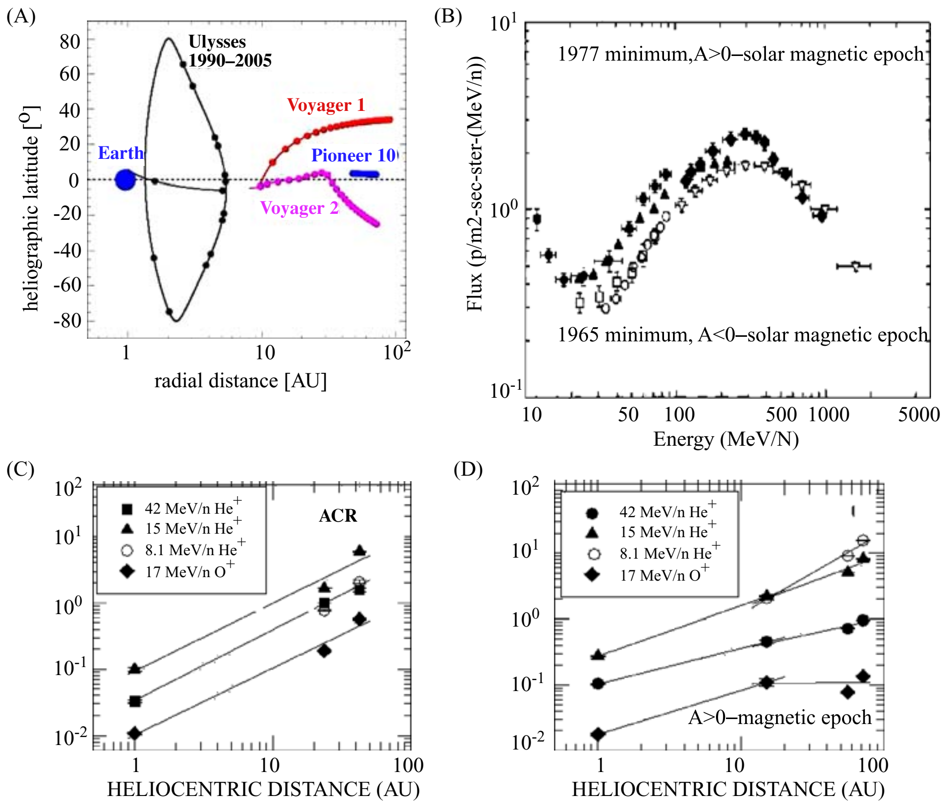

Figure 3. (A) Heliographic latitude and radial distance of Ulysses, V1, V2 and P10 from mid 1993 to 2005. Solid circles mark the start of each year. V1 crossed the termination shock (TS) at a distance of 94 AU in December 2004 (`http://www.nasa.gov/vision/universe/solarsystem/voyager_agu.html`). Galactic cosmic ray proton spectra (B), as measured by IMP during the 1960s and 1970s solar minima (Beatty *et al.*, 1985). Radial intensity distributions of cosmic rays for the $A < 0$ (C) and $A > 0$ solar magnetic epochs (D) have been determined by Fujii and McDonald (2005).

declining phase of solar cycle 22. The spacecraft is traveling since then in an elliptical orbit inclined at 80.2° to the solar equator and performed within 11 months a whole latitude scan of 160° up from 80°S to 80°N at solar minimum in 1994/1995 and at solar maximum in 2000/2001. Figure 4A displays the Ulysses and Earth trajectory during the minimum fast latitude scans. Marked by shading are the Ulysses polar passes, which are those periods during which the spacecraft is above 70 degrees heliographic latitude in either hemisphere. Figure 4 illustrates in its part (B) the expected variation of the proton spectrum. The expected proton spectra at 1 AU in the ecliptic and at 80° latitude are displayed together with the local interstellar spectrum (LIS). The model parameters have been chosen such that the 1 AU spectrum fits typical ecliptic 1 AU solar minimum spectra. At energies below several 100 MeV an increase by an order of magnitude was expected and the LIS

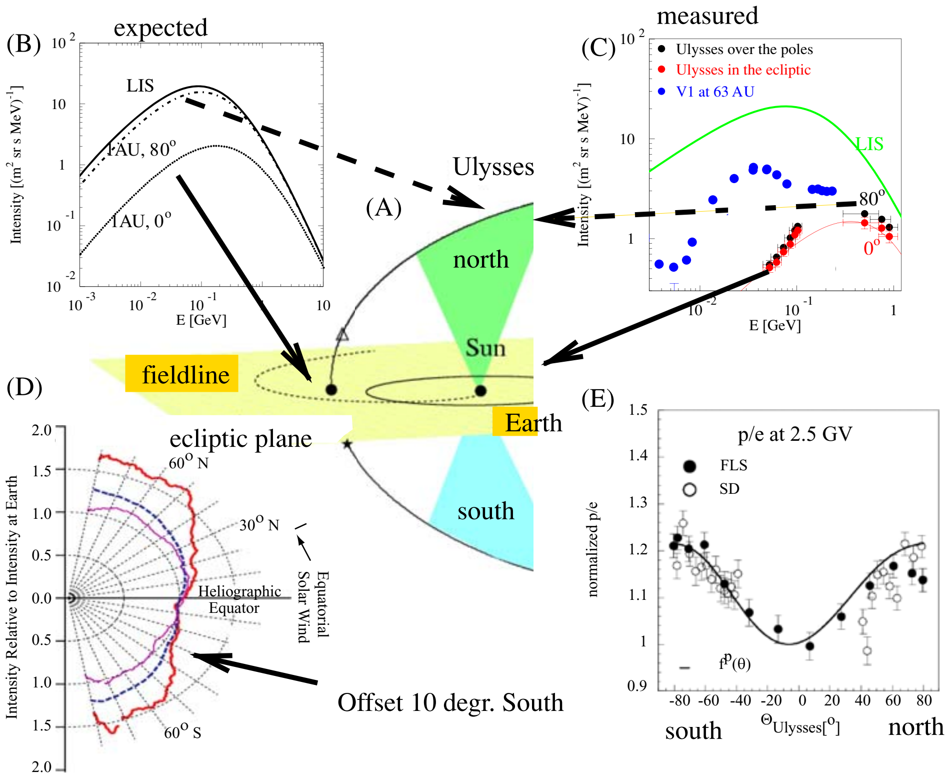

Figure 4. (A) Ulysses and Earth orbit during the first fast latitude scan in 1994/1995. (B) and (C) expected and measured spectra in the ecliptic and over the poles respectively. (D) Daily averages of >125 MeV protons measured at Earth and by Ulysses (red), showing a positive latitudinal gradient for galactic cosmic ray protons. (E) Proton to electron ratio as function of Ulysses heliographic latitude. The Figure is a composition from Heber and Potgieter (2000), McKibben *et al.* (1996), Heber *et al.* (1996b), and Heber *et al.* (1999).

should become almost unmodulated at polar latitudes. The Ulysses observations during solar minimum are given in panel (C) together with the Voyager observations at 63 AU. The red symbols and line correspond to the Ulysses observations and the calculation for the heliographic equator, respectively. The black symbols are Ulysses measurements above 70°. In contrast to the expectations the measured spectrum over the poles is still lower than the Voyager measurements and highly modulated. Thus Ulysses did not measure the LIS during the minimum of solar cycle 22 – with positive charged particles drifting inwards at polar regions – and led Heber *et al.* (1996a) to the conclusion that it is impossible to determine LIS in the inner heliosphere. Therefore the LIS will only be measurable by a space probe, like the Interstellar Probe (Liewer *et al.*, 2000) or an Interstellar Heliopause Explorer – investigated by ESA in 2003 (Leipold *et al.*, 2003) – to be sent far beyond the heliospheric termination shock.

Figure 4D displays nine day running averages of Ulysses to Earth-ratios of 35–70 MeV per nucleon protons, helium, and >100 MeV protons as a polar plot. The data are normalized during the equator crossing in March 1995. A constant ratio of one means a spherically symmetric cosmic ray distribution. From this Figure it is evident that 35–70 MeV protons do not show any significant latitudinal excess (pink curve), whereas >100 MeV protons (red curve) and 30–70 MeV per nucleon helium (blue curve) do. It was a big surprise when Simpson *et al.* (1996) and Heber *et al.* (1996a) reported that the flux of >100 MeV protons is not symmetric to the heliographic equator. They found a shift of $\sim 7^\circ$–10° of the minimum intensity into the southern hemisphere.

Although electrons are of minor importance for space climate, important information about heliospheric particle propagation can be derived from analyzing these data. Together with positrons they are unique, because (1) adiabatic energy losses are small and (2) information about the interstellar spectra can be derived independently from in situ measurements: Electrons and positrons undergo Bremsstrahlung and an inverse Compton effect in the galaxy (Webber, 1983, 1998; Strong, 2001). Since the drift pattern of electrons is opposite to the one of protons, one would expect that electrons have a different latitudinal gradient than protons. Unfortunately the Kiel Electron Telescope (Simpson *et al.*, 1992) on board Ulysses is the *only* experiment that measures GeV electrons continuously, so that the latitudinal electron distribution cannot be determined directly. Figure 4E displays how Heber *et al.* (1999) estimated the latitudinal gradient of electrons. These authors plotted the p/e-ratio as function of heliographic latitude. The line shown in panel (E) is the result of a fit to the proton distribution with latitude (not shown here). From the Figure it is obvious that the latitudinal variation of the e/p-ratio can also be approximated by that line. Therefore they concluded that the gradient of electrons is consistent with zero.

3. Solar Cycle Variation

Cosmic ray modulation during increased solar activity is characterized by several large steps that are easily recognized from observations at Earth and beyond, as shown in the right two panels of Figure 5 during the 1988, and 1998 period for example. These large steps are correlated with long-lasting intense magnetic fields in the outer heliosphere, called Global Merged Interaction Regions (Burlaga *et al.*, 1993). Cane *et al.* (1999) raised the question if such merging is necessary to modulate cosmic rays. They and Belov (2000) found a good correlation between the heliospheric magnetic field strength and the variation of galactic cosmic rays at Earth, indicating that the diffusion tensor should be correlated with the heliospheric magnetic field strength. Potgieter and Ferreira (2001) and Ferreira and Potgieter (2004) tested this idea using a full time-dependent numerical model with a diffusion coefficient changing with the phase of the solar cycle. They coupled the

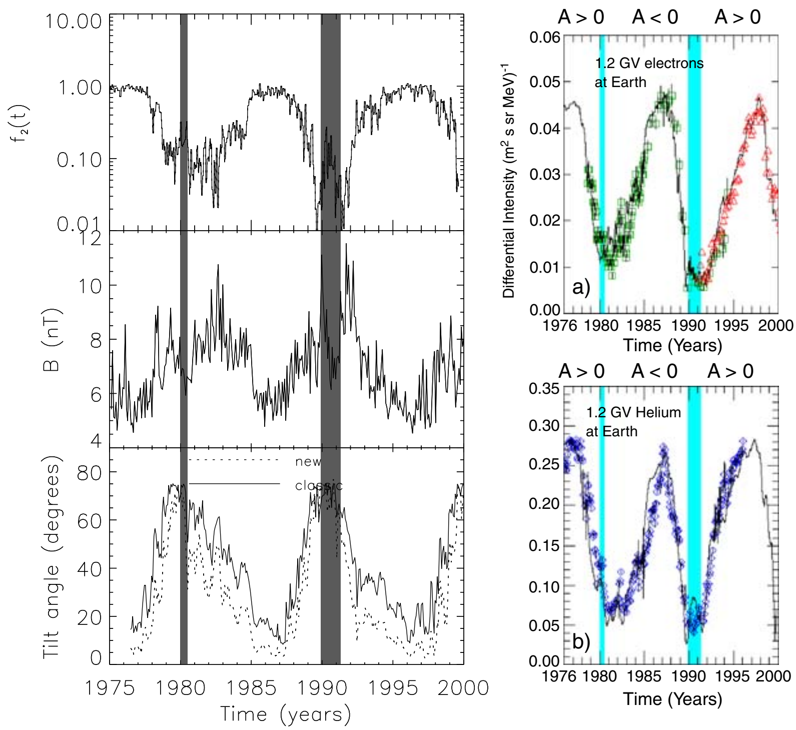

Figure 5. The left panels display from bottom to top the computed time history of the tilt angle, the measured magnetic field strength at 1 AU and the resulting variation of the diffusion tensor. On the right the measured and computed solar cycle modulation of 1.2 GV electron and helium are displayed (Potgieter and Ferreira, 2001).

diffusion tensor with the observed heliospheric magnetic field strength B and maximum latitudinal extension of the heliospheric current sheet (tilt angle α) so that variations are small for solar minimum, and are increasing with increasing solar activity. The time history of the tilt angle $\alpha(t)$ and of the heliospheric magnetic field B at Earth are displayed in the lower two panels of Figure 5 (left). The time dependence of the diffusion tensor is then expressed by $\kappa(t) \propto B^{\frac{\alpha}{n}}$, with n depending on the particle species and energy. Towards solar maximum, temporal changes in the diffusion coefficients essentially simulate step-like variations in the galactic cosmic ray intensities. In Figure 5 (right-hand panel) the results of this compound modeling approach are compared to the 1.2 GeV electron and helium observations. It is evident that the modulation amplitude, most of the steps, and the peaked and less peaked minima are reproduced, although some of the simulated steps do not have the correct magnitude and phase. It is also important to note that these authors could not use absolute identical parameters for electrons and protons, indicating that: (1) the diffusion coefficients in general may be different for the two species, (2) drifts are not yet handled correctly with increasing solar activity and/or (3) an additional charge-sign dependent processes may be contributing to modulation, e.g., magnetic helicity (Burger *et al.*, 1997).

Concerning (2) the importance of drifts over the 22-year solar magnetic cycle, measurements from the out-of-ecliptic Ulysses mission are crucial. The observed charge sign dependent latitudinal gradient at solar minimum are indicative for gradient and curvature drifts in the heliosphere.

Six years later when Ulysses performed another fast latitude scan Belov *et al.* (2003), Heber *et al.* (2003), and McKibben *et al.* (2003) reported a spherical symmetric cosmic ray distribution indicating that drifts are of minor importance around solar maximum. Ndiitwani *et al.* (2005) analyzed the e/p-ratio time profile during solar maximum and found that the no drift solution explains very well the solar maximum observations, but fails shortly before and after, indicating that the particle drift is an important factor for understanding solar modulation and that modulation models have to include all components used in Parker's transport Equation (1).

Several attempts have been made in the recent years to model the galactic cosmic ray intensities during the grand minima periods (see also Beer, 2006). These grand minima are characterized by low solar activity during several solar cycle as has been observed in the 17th century during the Maunder Minimum. Scherer and Fichtner (2004) used a dynamic multi fluid model of the global heliosphere (Fahr *et al.*, 2000). They found, that the variation of the heliospheric structure leads only to a small increase of galactic cosmic rays during the Maunder Minimum and therefore the diffusion tensor needs to be modified during such periods. In order to obtain more realistic results in future, Scherer and Ferreira (2005) combined successfully a dynamic multi fluid model of the global heliosphere with the compound particle transport code described above. Although it is beyond the scope of this paper to discuss all the effects of such an approach, it should be mentioned that for time scales longer than the length of the solar cycle several additional aspects have to be considered, like the particle transport in the heliosheath, the extrapolation of the current diffusion tensor and drift fields to different heliospheric conditions and the knowledge of the local interstellar spectra (Scherer *et al.*, 2004; Caballero-Lopez *et al.*, 2004; McCracken *et al.*, 2004).

4. Summary

In this paper, both the current knowledge and hypotheses about the modulation and the transport of cosmic rays in the heliosphere are reviewed. The transport theory aims at an understanding of all processes determining the propagation of cosmic rays in the solar wind plasma. Keys to fulfill this task are to measure the cosmic ray distribution in the three-dimensional heliosphere and to model the cosmic ray transport in the solar wind. The main unknowns in the models are the diffusion tensor, the importance of drifts and the local interstellar spectra. Drift effects depend on the charge sign of the particle and the polarity of the heliospheric magnetic field. Therefore it is important to analyze particles with opposite charge sign simultaneously. On the modelling side it is vital to include all modulation processes in transport models. Recent modelling has advanced to a self-consistent treatment of the dynamic heliosphere and the cosmic ray transport. This opens the unique opportunity to study long term modulation on time scales of centuries.

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