Cosmic Rays in the Dynamic Heliosphere

Marius S. POTGIETER

Unit for Space Physics, North-West University, 2520 Potchefstroom, South Africa

(Received: 27 August 2008 / Accepted: 15 December 2008)

The relation between the dynamics of the heliosphere, its shape and geometry, solar activity and cosmic ray variations is addressed. The global features of the heliosphere influence what happens inside its boundaries on a variety of time-scales. Galactic and anomalous cosmic rays are the messengers that convey vital information on global heliospheric changes in the manner that they respond to these changes. By observing neutral and charged particles, including cosmic rays, over a wide range of energies on various spacecraft and at Earth, a better understanding is gained about heliospheric phenomena including space weather and space climate. Causes of cosmic ray modulation and variability in the heliosphere are reviewed, with emphasis on the 11-year and 22-year solar activity cycles, step-modulation, charge-sign dependent modulation and particle drifts. Advances in this field will be highlighted such as the effects of the solar wind termination shock and the heliosheath on cosmic ray variability, also related to important recent observations in the heliosheath by the two Voyager spacecraft.

Keywords: Solar activity, solar wind, 22-year cycle, heliosphere, termination shock, heliosheath, cosmic rays.

1. Introduction

This review gives a brief discussion of the features of the global heliosphere and the relation between its dynamics, cosmic ray variations inside its boundaries and heliospace issues such as space climate. The large-scale features of the heliosphere including the termination shock (TS), the heliopause (HP) and the heliosheath, and in particular the variability of its global structure, influence what is happening inside its boundaries. This relates to solar activity and the variability of galactic cosmic rays (CRs) and anomalous cosmic rays (ACRs). The origin of the ACRs is briefly discussed with emphasis on their acceleration in the outer heliosphere. The causes of the CR cycles are reviewed, with emphasis on the 11-year and 22-year cycles, step modulation, charge-sign dependent modulation and particle drifts. The basic theory for the transport and modulation of CRs is given, with focus on the compound model for 22-year modulation. Advances in the field are briefly discussed in the context of what still are some of the major uncertainties and issues.

2. The Dynamic Heliosphere

The interstellar space between the Sun and nearby stars is filled with plasmas, magnetic fields, neutral and charged particles. The Sun moves through the interstellar medium (ISM) with a velocity of ~26 km.s^{-1} so that a heliospheric interface with the ISM is formed. The solar wind prevents this medium from flowing into the large volume dominated by the Sun, called the heliosphere. The heliosphere is considered to be a small but typical astrosphere. The extent of an astrosphere depends on the ram pressure of the stellar wind compared to the total pressure of the ISM. Because it is moving through the ISM the heliosphere is asymmetrical with respect to the Sun, with the tail region much more extended than the nose region, the direction in which it is moving. It extends over at least 500 AU in its equatorial regions and at least 250 AU in the polar plane. The main constituents of this interface with the ISM, shown in Figure 1, are the TS, the HP and a bow shock (BS), with the region between the TS and the HP defined as the inner heliosheath, with the outer heliosheath located between the HP and the BS. The latter is expected to be rather weak. The HP separates the solar wind and ISM so that it may be considered the outer boundary of the heliosphere. A prediction of MHD-HD modeling is that the solar wind creates a TS where it goes from supersonic (400−800 km.s^{-1}) to subsonic speeds between ~85 and ~105 AU [e.g. 1-3]. It is predicted that the heliospheric structure is dynamically asymmetric, yielding a ratio for the upwind-to-downwind TS distance of ~1:2. However, in the nose direction the TS movement is relatively limited. The heliosphere is elongated in its polar directions because of the latitudinal variation of the solar wind momentum flux. This asymmetry may become more pronounced during solar minimum conditions [4]. The TS position oscillates with solar activity, by as much as 3 AU in the upwind direction as it is driven outwards and by 5 AU backwards as it tries to recovery; in the tail direction this will be larger. The TS speed modifies the shock

Marius.Potgieter@nwu.ac.za

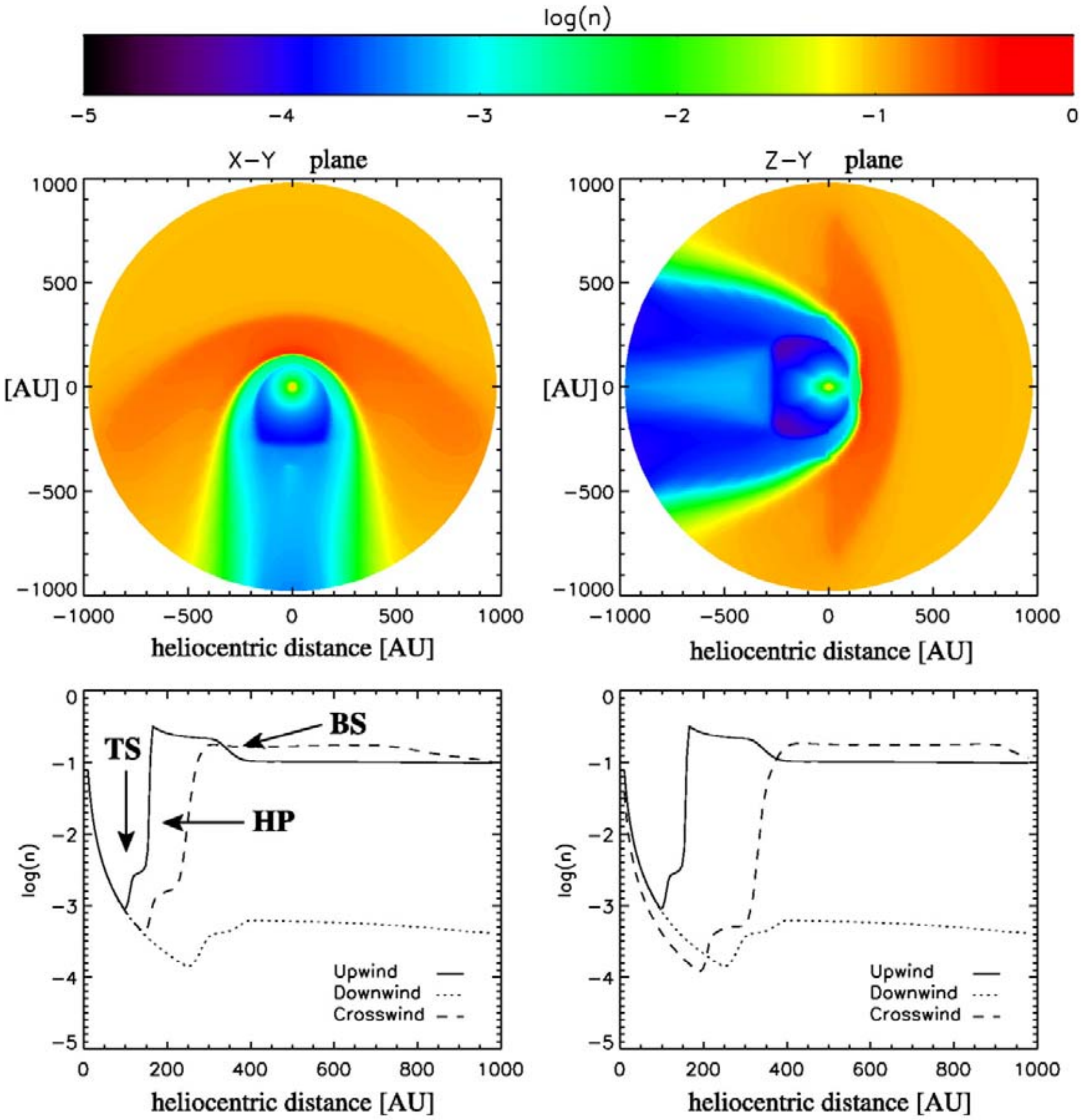

Fig. 1 Illustration of the heliospheric geometry, structure and boundaries using contour plots of the proton number density in the X-Y and Y-Z planes, obtained with a 3-dimensional HD model with the associated number density profiles in the heliospheric upwind, downwind, crosswind and polar directions in the lower panels [41].

strength (indicated by e.g., the compression ratio) by as much as 20% [5]. The shape of the HP is highly asymmetrical as shown in Figure 1; it is well defined in the nose direction, predicted to be at about 30-50 AU beyond the TS, but ill defined in the tail direction so that more modeling is required to understand these features.

The spacecraft Voyager 1 encountered the TS in December 2004 at a distance of ~94 AU from the Sun, at a polar angle of ~60º [6,7]. Its twin spacecraft Voyager 2 crossed the TS in August 2007 at 83.7 AU in the southern hemisphere, at ~120º and ~10 AU closer to the Sun than found by Voyager 1. This asymmetry could indicate an asymmetric pressure from an interstellar magnetic field, from transient-induced shock motion, or from the solar wind dynamic pressure. Stone et al. [8] reported that the intensity of 4-5 MeV protons accelerated by the TS near Voyager 2 was three times that observed concurrently by Voyager 1, indicating differences in the TS at the two locations. Companion papers in Nature (July 2008) reported on the plasma, magnetic field, plasma-wave and lower energy particle observations at the TS. These observations are of major importance and quite an accomplishment for this 30 year long mission.

Modeling predicts that the interstellar environment of the heliosphere influences its shape and structure e.g. [3,9,10] and that the flux of CRs in the heliosphere is affected by changes of the heliospheric geometry. This is an interesting contemporary research topic, and relates to what is called space climate, in additional to the well-known topic of space weather, which focuses on

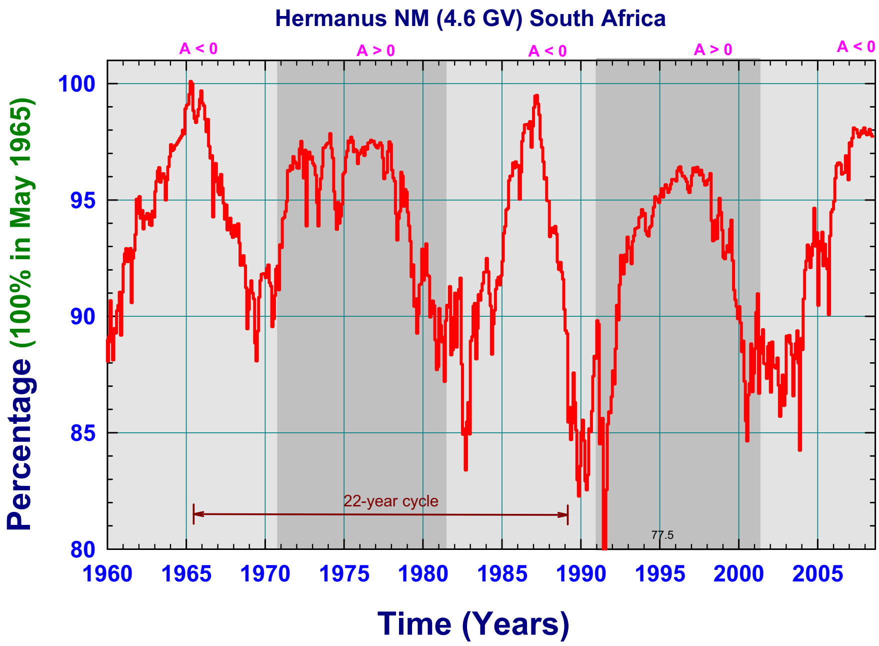

Fig. 2 The Hermanus Cosmic Ray Monitor in South Africa, illustrating the 11-year and 22-year cycles and the large step-like decreases and recoveries of galactic cosmic ray intensities at Earth.

solar and inner heliospheric conditions. In recent years, the very long-term variability (thousands of years) of the CR flux has become important for the interpretation of the abundances of cosmogenic isotopes in cosmochronic archives (from ice cores) and for its potential impact on the terrestrial climate. The galactic CR flux is not only varying due to the solar activity-induced changes of the solar wind and heliospheric magnetic field (HMF) but also in response to the changing state of the ISM surrounding the heliosphere. For detail, the reader is referred to the comprehensive review by [11].

3. Cosmic Rays in the Heliosphere

Cosmic rays are charged particles with energies ranging from ~1 MeV to as high as 10^{21} eV. Charged particles present in the heliosphere are classified in four main populations: (1) Galactic CRs which originated far outside the heliosphere, probably accelerated during supernova explosions. When arriving at Earth, these particles are composed of ~98% nuclei (mostly protons), fully stripped of all their electrons, and ~ 2% electrons and fewer positrons. (2) Solar energetic particles which originate mainly from solar flares, coronal mass ejections and shocks in the interplanetary medium. They occur sporadically, and may have energies up to several GeV, observed in the inner heliosphere usually only for several hours mainly during solar maximum activity. These events are directly linked to what is called space weather. (3) The anomalous components which were originally interstellar neutral atoms that got singly ionized relatively close to the Sun. They are transported as so-called pick-up ions to the outer heliosphere where they get accelerated up to a ~100 MeV through various processes. (4) The Jovian electrons which dominate the low energy electron spectrum up to 30 MeV within the first 10 AU from the Sun.

Anomalous cosmic rays were discovered in the early 1970s, with energies $E \approx$ 10-100 MeV/nuc [12] and a composition consisting of hydrogen, helium, nitrogen, oxygen, neon and argon. They get accelerated in the outer heliosphere, at the TS and beyond. For a review of the main features of these ACRs, see [13] and for a review of energetic neutral atoms, see [14]. The acceleration mechanism has become an issue: Immediately upon ionization, the interstellar particles are picked up by the solar wind and acquire energies of about 1 keV/nucleon, to become ACRs; these pick-up ions must be accelerated by four orders of magnitude to be observed at the mentioned energies. The principal acceleration mechanism to accomplish this remarkable feature has been considered to be diffusive shock acceleration [15]. However, at the location of the TS observed by the two Voyager spacecraft, there was no *direct* modulation evidence of this process occurring for ACRs. This suggests that the source is elsewhere on the TS or in the heliosheath, as is further discussed below. The higher energy ACRs thus seems disappointingly unaffected by the TS. On the other hand, low-energy ions (E < 3 MeV/nucleon) are clearly accelerated [6,7,8]. These unmistakably accelerated particles have since become known as termination shock particles. They are also expected to originate as interstellar neutral gas but seem to have no obvious connection to the ACRs.

3.1 Cosmic ray variability

Life on Earth is protected against CRs by three space 'frontiers', the first one arguably the least appreciated: (1) The dynamic heliosphere with the solar wind and the accompanying turbulent heliospheric magnetic field (HMF). (2) The Earth's magnetic field, with its dynamic character, e.g., large decreases have been occurring over southern Africa over the past decades. This means that significant changes in the geomagnetic cut-off rigidity for CRs occur, sufficiently large over the past 400 years so that the change in CR flux impacting the Earth may approximate the relative change in flux over a solar cycle [16]. The magnetosphere withstands the space weather changes that the Sun produces, and also reverses its magnetic polarity on a very long-term (the last one was ~780 000 years ago, so that the next reversal is considered long overdue). (3) The atmosphere with all its complex physics and chemistry. The CR intensity decreases exponentially with increasing atmospheric pressure.

The most important variability time scale related to solar activity is the 11-year cycle. This quasi-periodicity is convincingly reflected in the records of sunspots since the early 1600's, and other solar activity indices and also in the galactic CR intensity observed at ground and sea level especially since the 1950's when neutron monitors (NMs) as CR detectors were widely deployed as part of the International Geophysical Year (IGY 1957). This is shown in Figure 2. The period 2006-2008 has been celebrated as the 50th anniversary of the IGY and is called the International Heliophysical Year (www.ihy2007.org). Another important cycle in Figure 2 is the 22-year cycle shown, directly related to the reversal of the solar magnetic field during each period of extreme solar activity. There are several additional short periodicities evident in NM and other CR data, e.g., the 25-27-day variation caused by the rotational Sun, and the daily variation caused by the Earth's rotation. These variations seldom have magnitudes of more than 1% with respect to the previous quiet times. The well-studied corotating effect is caused mainly by interaction regions (CIRs) created when a faster solar wind overtakes a previously released slow solar wind. They usually merge as they propagate outwards to form various types of interaction regions, the largest ones are known as global merged interaction regions (GMIRs), discussed further below. They are related to what happened to the solar magnetic field at an earlier stage and are linked to coronal mass ejections (CMEs) that are always prominent with increased solar activity but dissipate during solar minimum. These GMIRs propagate with the solar wind speed into the heliosheath. Isolated GMIRs may cause very large decreases (as shown for 1991 in Figure 2) superimposed on the 11-year cycle but they usually lasts only several months. A series of GMIRs may contribute significantly to 11-year modulation during periods of increased solar activity in the form of relatively large discrete steps, increasing the overall amplitude of the 11-year cycle [17].

3.2 Space Climate

The galactic CR flux is also not expected to be constant along the trajectory of the solar system in the galaxy. Interstellar conditions, also locally, should differ significantly over time-scales of millions of years, such as when the Sun moves in and out of the galactic spiral arms [18]. It is accepted that the concentration of ^{10}Be nuclei in polar ice exhibits temporal variations in response to changes in the flux of the primary CRs over hundreds of years ([19] and references therein).

Exploring CR modulation over time scales of hundreds to thousands to millions of years, during times when the heliosphere was significantly different from the present epoch, is a very interesting development and keenly studied. Marsh and Svensmark [20] found a correlation between the flux of CRs and the global average of low cloud cover on Earth. Besides solar activity as the internal driver of heliospheric dynamics, and the obvious space weather connection, the structure of the heliosphere is also determined by external factors caused by a changing interstellar environment [9]. Shaviv [18] speculated that the major ice ages on Earth might even be triggered by encounters of the heliosphere with its galactic environment, given the CR-clouds relation. As reviewed by [11], computations indicate that the galactic CR flux reaching the heliosphere is indeed not constant over very long time scales e.g., the galactic spiral arms crossings where a large number of supernovae occur [21]. This kind of variation in galactic CR intensity is significant so that it should have a measurable effect on space climate in the heliosphere and a clear imprint on the terrestrial archive. A full understanding of CR variability in this context is a major research goal. It is essential to fully understand the dynamics of the heliosphere, the time variation of local ISM, and beyond, in order to appreciate the variations of the order of thousands of years, and much longer, that seem to exist in the flux of galactic CRs. The effects of the dynamics of the heliosphere on CR modulation and subsequently on climate has been studied quantitatively only recently, an aspect that will become increasingly important.

4. The Theory and Modeling of the Heliospheric Modulation of Cosmic Rays

Models for the global modulation of CRs in the heliosphere are based on numerical solutions of Parker’s [22] time-dependent transport equation:

$$\frac{\partial f}{\partial t} = -(\mathbf{V} + \langle \mathbf{v_D} \rangle) \cdot \nabla f + \nabla \cdot (\boldsymbol{K}_s \cdot \nabla f) + \frac{p}{3}(\nabla \cdot \mathbf{V})\frac{\partial f}{\partial p} + J_{source}, \quad (1)$$

where $f(\mathbf{r},p,t)$ is the cosmic ray distribution function; p is momentum, $\mathbf{r}$ is position, $\mathbf{V}$ is the solar wind velocity and t is time. Terms on the right-hand side represent respectively convection, gradient- and curvature-drifts, diffusion, adiabatic energy changes, and a source function e.g., for the anomalous cosmic ray component or the Jovian electron source. The tensor $\boldsymbol{K}_s$ consists of a parallel diffusion coefficient ($K_{||}$) and two perpendicular diffusion coefficients, one in the radial direction ($K_{\perp r}$) and one in the polar direction ($K_{\perp\theta}$). The pitch angle averaged guiding center drift velocity for a near isotropic cosmic ray distribution is given by $\langle \mathbf{v}_D \rangle = \nabla \times (K_A \mathbf{e}_B)$, with $\mathbf{e}_B = \boldsymbol{B}/B_m$ and B_m the magnitude of the modified background HMF, with K_A the off-diagonal element of the full diffusion tensor describing gradient and curvature drift. For detailed information, see the review [23].

Realistic modeling of the modulation of CRs in the heliosphere requires key but mostly unknown information. First, the local interstellar spectra for the different CR species are needed as initial conditions at the assumed outer heliospheric boundary. Little is known about most of these galactic spectra at energies below a few GeV because of heliospheric modulation. Second, the structural shape and geometry of the heliosphere must be specified, for example, where the TS and the HP is located. Third, knowledge is required about the global, 3-dimensional solar wind and HMF profiles. Presently, the solar wind profile can be specified with detail in the inner heliosphere, while for the HMF it was realized that it may not be approximated well enough by a rotating dipole so that more advanced approaches are explored with interesting consequences for CR modulation [24]. The wavy heliospheric current sheet (HCS) has turned out to be one of the most successful modulation parameters, once it was realized that gradient and curvature drifts should play an important role [25]. The "tilt angle" α of the HCS has become a prime indicator of solar activity from a CR modulation point of view and it is widely used in CR data interpretation; for solar minimum conditions α = 10º and for moderate maximum conditions α = 75º (quake.stanford.edu/~wso). The two magnetic polarity cycles are usually indicated by A > 0 (1970's, 1990's) and A < 0 (1980's, 2000's). The modulation effects of the HCS and drifts, the subsequent 22-year cycle and charge-sign dependence have been studied in detail [26,27]. Periods of maximum CR modulation are more complex; they may last only three years (e.g., 1969–1971), or up to six years (e.g., 1979–1984), or may temporarily be dominated by a massive CR decrease as in 1991 (see Figure 1). Underlying patterns are obscured by an apparent randomness which makes modeling of long-term modulation difficult. Nevertheless, there exist several concepts (not yet fully developed theories) on how modulation occurs over 11 years, the most recent work by [27]. Fourth, a major issue in modulation modeling is the spatial, energy (or rigidity) and time-dependence of the modulation process as determined by the diffusion coefficients. As yet, no *ab initio* modulation theory exists, one in which the diffusion coefficients are determined on the basis of our understanding of heliospheric turbulence and diffusion. For example, the slope of the turbulence spectrum determines the energy dependence of the scattering mean free path with respect to the background HMF, obviously of vital importance to CR propagation studies. The time dependence of the transport of energetic particles results from the time dependence of the solar wind and HMF turbulence. Using basic and phenomenological approaches, progress is being made in this vital important field of heliospheric physics [28,29; see 23 for a review].

An important advance in the modeling of CR modulation is the development of self-consistent "hybrid" models that describe the dynamical structure of the heliosphere embedded in the local ISM and simultaneously allow for a kinetic treatment of CR transport and modulation. Much can be learned about astrospheres in general from these dedicated modeling studies of the heliosphere [30, 31, 32].

4.1 The 11-year and 22-year cycles, and step modulation

Significant progress has been made in solving Eq.(1) numerically with increasing sophistication and complexity, also time-dependently for both the A > 0 and A < 0 magnetic polarity cycles, using as main input parameters the time varying HCS tilt angles and the time varying measured HMF values at Earth (NSSDC COHOWeb: http://nssdc.gfc.nasa.gov/cohoweb). A basic departure point for the time-dependence of global, 11-year modulation is that propagating barriers (solar wind and magnetic field structures inhibiting the easy access of CRs) are formed and later dissipated in the heliosphere following the solar activity cycle. This is especially applicable to the phase of the solar activity cycle before and after solar maximum conditions when large steps in the particle intensities occurred shown in Figure 2. As mentioned above, a wide range of interaction regions occur in the heliosphere with GMIRs being the largest, introduced by [33]. The paradigm on which this modulation 'barrier' is based is that interaction (and rarefaction) regions form with increasing radial distance from the Sun. This happens when two different solar wind speed regions become radially aligned to form an interaction region when the fast one runs into the slower one, resulting in compression fronts with forward and backward shocks. When these narrow interaction regions propagate outwards and expand, they may wrap almost around the Sun to become CIRs. When they merge and interact, merged interaction regions and finally GMIRs are formed beyond 5-10 AU. Potgieter et al. [34] illustrated that the affects of GMIRs on 11-year modulation depend on their rate of occurrence, the speed with which they propagate, their spatial extent and amplitude, especially their latitudinal extent (to disturb global drifts), and the background modulation conditions they encounter and importantly on the radius of the heliosphere (i.e., how long they stay inside the modulation volume). Drifts, on the other hand, dominate the solar minimum modulation periods up to four years so that during an 11-year cycle a transition must occur (depending on how solar activity develops and declines) from a period dominated by drifts to a period dominated by these propagating structures. The largest of the step decreases and recoveries shown in Figure 2 are caused by these GMIRs. The 11-year and 22-year cycles together with the step-like modulation evident in Figure 2 are good examples of the interplay of the main modulation mechanisms; global gradient and curvature drifts playing a dominant role during periods of minimum solar activity in conjunction with convection, diffusion and adiabatic energy losses. The role of gradient, curvature and current sheet drifts in long-term CR modulation was illustrated by [17] who showed that it was possible to simulate, to the first order, a complete 22-year modulation cycle by including a combination of drifts with time-dependent tilt angles and GMIRs [35, and references therein]. Following up on these earlier modeling efforts, a self-consistent CR hydrodynamic model was used by [36] who showed that GMIRs undergo considerable decay in both amplitude and width when encountering the solar wind TS, and that they can exist well into the heliosheath. This aspect of heliospheric physics is another important development. For a recent contribution of what may happen in the heliosheath, see e.g. [37, 56].

Cane et al. [38] pointed out that the step decreases observed at Earth could not be primarily caused by GMIRs because they occurred well before GMIRs could form. Instead, they suggested that time-dependent global changes in the HMF over an 11-year cycle might be responsible for long-term modulation. Ferreira and Potgieter [27] combined these changes with time-dependent drifts to simulate 11-year modulation in the heliosphere, naming it the compound modeling approach. It was assumed that all the diffusion coefficients change time dependently proportional to $B(t)^{-n}$, with $B(t)$ the observed solar magnetic field at Earth, and $n(P,t)$ a function of rigidity and the HCS tilt angle (time dependence related to solar activity). These changes are then propagated outwards at the solar wind speed to form propagating modulation 'barriers' throughout the heliosphere, changing with the solar cycle. With $n = 1$, and $B(t)$ changing by an observed factor of 2 over a solar cycle, this approach resulted in a variation of the diffusion coefficients by a factor of 2 only, which is perfect to simulate the 11-year modulation at NM energies at Earth, as seen in Figure 2, but not at all for lower rigidities. In order to reproduce spacecraft observations at $E < \sim 1$ GeV, n must depend on time (solar activity) and rigidity. Using the HCS tilt angles as the only time-dependent modulation parameter resulted in compatible with solar minimum observations but not for intermediate to solar maximum conditions; the computed modulation amplitude was too small. They illustrated that HCS drifts alone cannot be responsible for the modulation of galactic CRs over a complete 11-year cycle. Using the compound approach resolved this problem. Applied at Earth and along the Ulysses and Voyager 1 and 2 trajectories, this approach is remarkably successful e.g., when compared with 1.2 GV electron and helium observations at Earth, it produces the correct 22- year modulation amplitude and most of the modulation steps. Some of the simulated steps did not have the correct magnitude and phase, indicating that refinement of this approach is needed by allowing for merging of the propagating structures. However, solar maximum modulation could be largely reproduced for different CR species using this relatively simple concept, while maintaining all the other major modulation features during solar minimum, such as charge-sign dependence will be discussed below.

4.2 Charge-sign dependent modulation

An important accomplishment is that this compound modeling approach also explains the observed charge-sign dependent modulation, from minimum to maximum solar activity. This type of modulation is one of the important features of CR modulation because it is a direct indication of gradient, curvature and current sheet drifts in the heliosphere. It was also found that during periods of large solar activity, drifts must be reduced additionally to other time-dependent changes in order to describe the mentioned observations and the electron to He intensity ratio at Earth during the period when the HMF polarity reverses. Ndiitwani et al. [39] calculated the percentage drifts required over a full modulation cycle, including extreme solar maximum, to find compatibility between the compound modeling approach and the observed electron to proton ratio from the KET on board Ulysses. They found that little drifts are required during solar maximum activity in contrast to close to 90% at solar minimum activity. Drifts had to be reduced from a 50% level at the beginning of 1999 to a 10% level by the end of 1999, to vanish during 2000 (solar maximum). This indicates that in order to produce realistic charge-sign dependent modulation during extreme solar maximum conditions, the heliosphere must become diffusion dominated. For detailed discussions of these observations and corresponding modeling, see [23].

5. Modulation in the heliosheath

Observations by the Ulysses, Pioneer, Voyager, IMP, SOHO and other missions, and now also PAMELA [55], have contributed significantly to understand the spatial dependence and time evolution of the main modulation mechanisms. A major contribution was the confirmation that **V** is not uniform over all latitudes but that it divides into the fast and slow wind regions during solar minimum conditions [40]. The next challenge is to understand the complexity of the solar wind flow and the imbedded magnetic field in the heliosheath, where **V** obtains strong latitudinal and azimuthal components. Apart from the convection caused by the solar wind, the divergence of **V** is equally important because it describes the adiabatic energy changes of CRs. When it is positive, as in most of the heliosphere, CR ions experience large energy loses resulting in a characteristic spectral shape below a few

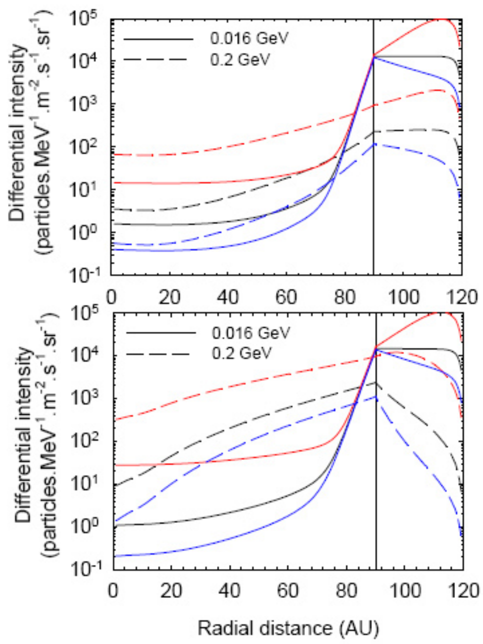

Fig. 3 Radial intensity profiles for anomalous protons with three scenarios for the divergence of the solar wind speed in the heliosheath during solar minimum conditions in the A > 0 (top panel) and A < 0 (bottom panel) magnetic polarity epochs [41]. See accompanying text.

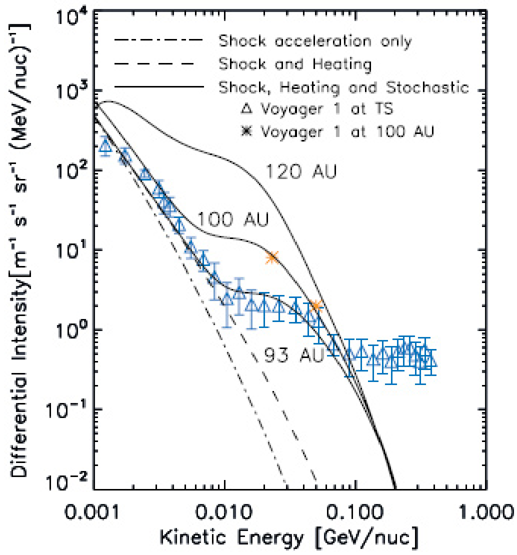

Fig. 4 Computed spectra for singly ionized anomalous He at the TS (93 AU) and in the heliosheath for three acceleration scenarios: (1) diffusive shock acceleration only (dashed dotted line), (2) diffusive shock acceleration and adiabatic heating (dashed line) and (3) shock acceleration, heating in the inner heliosheath and acceleration of a stochastic nature (solid lines) [44].

hundred MeV in the inner heliosphere. Right at the TS it is negative and beyond the shock it may vary between positive and negative, with interesting effects for ACRs, such as a significant increasing intensity beyond the TS caused by adiabatic heating [41]. In Figure 3, an example of the numerical solutions of Eq. (1) is shown to illustrate the radial intensity profiles for anomalous protons, respectively from the inner to the outer heliosphere with three scenarios for the divergence of **V** in the heliosheath. The solutions are for the equatorial nose direction of the heliosphere during solar minimum activity conditions for the two magnetic field polarities. The TS position is indicated with a vertical line, black lines represent the reference solutions with $V \propto 1/r^2$ in the heliosheath, red lines for $V \propto 1/r^8$ and blue lines for $V \propto r^2$.

Langner and Potgieter [42] also studied charge-sign dependent effects in the outer heliosphere and came to the conclusion that drifts may be significantly altered beyond the TS, a topic that needs further investigation at both the fundamental and modeling level.

The contribution of additional terms to Eq. (1) also have to be investigated, e.g., if the Alfven speed would no longer be negligible compared to the solar wind speed [43] as may happen in the heliosheath. Recently, Ferreira et al. [44, references herein] illustrated that by considering diffusive shock acceleration at the TS, adiabatic heating and stochastic acceleration together beyond the TS, the ACRs may get accelerated up to the HP and may thus escape the heliosphere to be the dominant low energy (E < 50-100 MeV) CR component in the local interstellar medium, obscuring the value of the galactic CR spectra at these energies for several particle species inside the heliosphere. Figure 4 depicts the computed spectra for singly ionized anomalous He at the TS (93 AU) and beyond for three acceleration scenarios: (1) Diffusive shock acceleration only (dashed-dotted line). (2) Diffusive shock acceleration and adiabatic heating (dashed line). (3) Shock acceleration, adiabatic heating and stochastic acceleration (solid lines), shown at the shock (bottom solid line), at 100 AU and 120 AU (top solid line). In comparison the observed Voyager 1 spectra from 16 to 23 January 2005 at the observed termination shock are shown as the triangles, and the asterisk symbols are for Voyager 1 observations at 100 AU http://voycrs.gsfc.nasa.gov).

While the high-energy part of the galactic CR spectrum is well observed, its spectral shape at $E < \sim 1$ GeV.nuc^{-1} is still not known. Recent in situ measurements made with the Voyager spacecraft in the heliosheath have added further constraints on the local interstellar spectra for galactic CRs at these low energies. Scherer et al. [45]

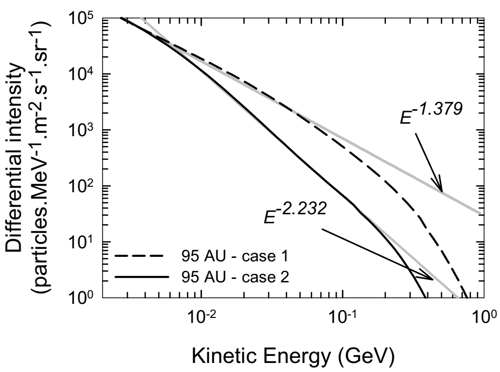

Fig. 5 Accelerated ACR protons at the TS position. Grey lines are normalized power law functions fitting the spectra at the TS position. Note the ‘break’ in the spectrum for case 2 [47].

argued that these observations also suggest how the low-energy proton part is influenced locally and perhaps even globally in the Galaxy. The measured flux of ACRs in the heliosheath is unexpectedly high compared to expectations before Voyager 1 reached the TS, which might be a temporal effect or due to an additional acceleration beyond the termination shock. Combining this finding with recent model results for astrospheres [46] immersed in different interstellar environments shows that the astrospheric ACR fluxes of solar-type stars can be a hundred times higher than thought earlier and consequently their total contribution to the lower end of

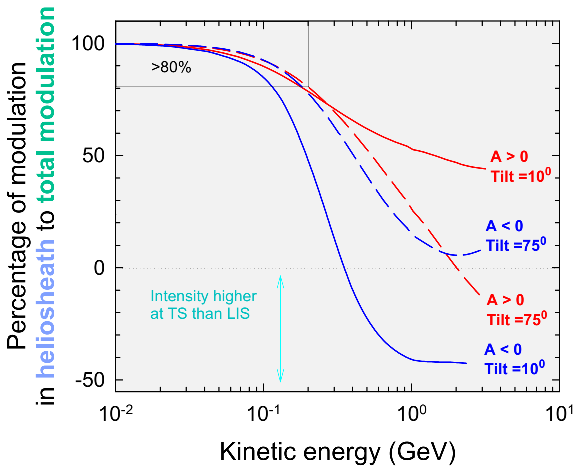

Fig. 6 Computed percentage of CR modulation in the heliosheath with respect to the total modulation (between 120 and 1 AU) as a function of kinetic energy for the two magnetic polarity cycles (A > 0 and A < 0), for solar minimum (α = 10º) and for moderate maximum (α = 75º) conditions, in the equatorial plane in the nose direction of the heliosphere. Negative percentages mean that the CRs can be reaccelerated at the TS [52].

the interstellar spectra can be significant.

Langner and Potgieter [47] showed that the acceleration and modulation effects of a changing radial perpendicular diffusion as function of latitude in the outer heliosphere and along the TS position could change the spectral indices of the computed TS spectra. It is found that although the compression ratio was specified as s = 2.5 in the model, the compression ratio calculated from the ACR spectral indices is much lower (for ACR HE spectra, s = 1.2; for ACR proton spectra s = 1.9) when radial perpendicular diffusion is made strongly latitude dependent. The increasing radial perpendicular diffusion with heliolatitude results in a spectral break in the spectrum at the TS at ~6.0 MeV, changing from $E^{-1.38}$ to $E^{-2.23}$ for ACR protons, and at ~3.0 MeV, changing from $E^{-1.38}$ to $E^{-2.30}$ for ACR Helium. Shown in Figure 5, this approach therefore predicts a definite 'break' in the spectral power law at an energy at which TS acceleration of ACRs become less effective, as Voyager 1 observations indicate.

McComas and Schwadron [48] proposed that ACRs could also be accelerated at the flanks of the TS where connection time is sufficient for acceleration to ACR energies. The injection into the TS may be more efficient at the flanks where the shock angle is less perpendicular than it is at the nose region. Since ACRs are coming from the flanks their flux continues to increase beyond the TS, and the ACR spectrum must gradually unfold only as Voyager 1 advances deeper into the heliosheath and becomes magnetically connected to the flanks [49,50].

This field of research, with the focus on the outer heliosphere, in particular the inner heliosheath, is currently highly relevant, with several issues to be clarified [51].

Considering the modulation shown in Figure 2, the question that is relevant within the context of present Voyager 1 and 2 observations is how much modulation occurs inside the heliosheath and where does the CR modulation actually begin? Does it begin at the HP and acts the heliosheath as a kind of modulation 'barrier'? Or could it be that CR modulation sets on beyond the HP? The process is of course highly energy dependent so the answer must depend on the considered energy of the CRs. Presently, the HP is generally assumed be the 'outer boundary' for CR modulation. An illustrative example of the amount of modulation that CR protons may experience in the heliosheath in the nose direction is shown in Figure 6. The percentage of modulation in the equatorial plane in the heliosheath is given with respect to the total modulation (between 120 AU and 1 AU) as a function of kinetic energy for both polarity cycles (A > 0 and A < 0), for solar minimum (α = 10°) and moderate maximum (α = 75°) conditions [52, 53]. Evidently, larger than 80% modulation may occur in the heliosheath for both polarity cycles at E < ~0.02 GeV. For all four the conditions, the modulation in the heliosheath will eventually reach 0% (not shown) but at different energies, indicating that heliosheath modulation may differ significantly with energy as well as with drift cycles. The amount of modulation inside the heliosheath will not be known precisely until the local interstellar spectra are being observed. How much gradient and curvature drifts actually occur in the heliosheath is still unanswered. The negative percentages indicate that the intensity may actually increasing in the heliosheath as one moves inward from the HP toward the TS because of the re-acceleration of CRs at the TS. This of course depends on many aspects, in particular the TS compression ratio. From this it is clear that the heliosheath, with its interesting physics, plays an important role in CR modulation.

Another active field of research is that of energetic neutral atoms (ENAs) produced by charge exchange between fast ions and slow neutral atoms. A major part of the ENA flux comes from regions where both the flux of parent ions and the neutral atom density are high; at the energies that will be measured by the IBEX mission, the main contribution is expected from the (inner) heliosheath [54].

6. Summary

Heliospace physics forms part of the universal physical processes that can be used to gain better understanding of the features and characteristics of geospace and galactic space. The heliosphere is a typical small astrosphere. Cosmic ray variability contributes to the understanding of the importance of the complex field of space weather. Only recently has the dynamics of the heliosphere been studied and appreciated, in particular its role in cosmic ray variability and ultimately its role in space climate [11].

Heliospheric physics, and in particular, the outer heliosphere with the solar wind TS and heliosheath, has become most relevant and is being actively studied. The recent crossings of the TS by the two Voyager spacecraft have been a major accomplishment that has renewed the interest in CR modulation and the physics of the heliosheath. Observations of galactic and anomalous CRs in the outer heliosphere, together with the solar wind and magnetic field, have also caused new controversies and scientific issues. The acceleration of the anomalous CRs at the TS was thought to be caused mainly by diffusive shock acceleration but new information and modeling show that neglected mechanisms such as stochastic acceleration and solar wind adiabatic heating may be equally important.

Several challenges need to be studied: What is the global strength and structure of the TS? How are energetic particles accelerated at and beyond the TS? What are the global properties of the plasmatic flow beyond the TS and in the heliotail? How does the interstellar flow interact with the heliosphere beyond the HP? Understanding this physics will give the theoretical and modeling tools to study broader issues in both heliophysics and astrophysics.

The study of the heliosheath, the heliopause and the heliospheric interface with the local interstellar medium and how galactic and anomalous cosmic rays respond to the global dynamics thereof, will be one of the prominent heliospace research topics for the coming years.

7. Acknowledgements

The financial support by the South African National Research Foundation (NRF) and the SA Centre for High Performance Computing (CHPC) is valued. The author is also grateful for many delightful and informative discussions on the outer heliosphere with Stefan Ferreira, Ingo Büsching, Klaus Scherer, Horst Fichtner, and Bill Webber.

[1] K. Scherer and H.-J. Fahr, Geophys. Res. Lett. **30**, 17:1 (2003).

[2] H. J. Fahr, Adv. Space Res. **34**, 3 (2004).

[3] Y. G. Malama, V. V. Izmodenov and S. V. Chalov, Astron. Astrophys. **445**, 693 (2006).

[4] S. E. S. Ferreira and K. Scherer, Astrophys. J. **642**, 1256 (2006).

[5] Y. C. Whang, AIP Conf. Proc. **719**, 22 (2004).

[6] E. C. Stone *et al.,* Science, **309**, 2017 (2005).

[7] R. B. Decker *et al*., Science **309**, 2020 (2005).

[8] E. C. Stone *et al.,* Nature, 454, 71 (2008).

[9] K. Scherer *et al*., Adv. Space Res. **41**, 1171 (2008).

[10] H.-R. Müller *et al.,* Astrophys. J. **647**, 1491 (2006).

[11] K. Scherer *et al.,* Space Sci. Rev. **127**, 327 (2006).

[12] M. Garcia-Munoz, G. M. Mason and J. A. Simpson, Astrophys. J. **182**, L81 (1973).

[13] H. Fichtner, Space Sci. Rev. **95**, 639 (2001).

[14] H. J. Fahr, H. Fichtner, and K. Scherer, Rev. Geophys. **45**, 1 (2007).

[15] J. R. Jokipii, J. Geophys. Res. **91**, 2929 (1986).

[16] M. A. Shea and D. F. Smart, Adv. Space Res. **34**, 420 (2004).

[17] J. A. le Roux and M. S. Potgieter, Astrophys. J. **442**, 847 (1995).

[18] N. J. Shaviv, New Astron. **8**, 39 (2003).

[19] J. Masarik and J. Beer, J. Geophys. Res. **104**, 12099 (1999).

[20] N. Marsh and H. Svensmark, Space Sci. Rev. **94**, 215 (2000).

[21] I. Büsching and M. S. Potgieter, Adv. Space Res. **42**, 504 (2008).

[22] E. N. Parker, Planet. Space Sci. **13**, 9 (1965).

[23] B. Heber and M. S. Potgieter, Space Sci. Rev **127**, 117 (2006).

[24] R. A. Burger, T. P. J. Krüger, M. Hitge, N. E. Engelbrecht, Astrophys. J. **674**, 511 (2007).

[25] J. R. Jokipii, E. H. Levy and W. B. Hubbard, Astrophys. J. **213**, 861 (1977).

[26] S. E. S Ferreira and M. S. Potgieter, Adv. Space Res. **32**, 657 (2003).

[27] S. E. S Ferreira and M. S. Potgieter, Astrophys. J. **603**, 744 (2004).

[28] J. W. Bieber, Adv. Space Res. **32**, 549 (2003).

[29] A. Shalchi *et al.,* Astrophys. J. **230**, 642 (2006).

[30] H. Fichtner, Adv. Space Res. **35**, 512 (2005).

[31] S. E. S. Ferreira, K. Scherer and M. S. Potgieter, Adv. Space Res. **41**, 351 (2008).

[32] N. V. Pogorelov, G. P. Zank and T. Ogino, Adv. Space Res. **41**, 306 (2008).

[33] L. F. Burlaga, F. B. McDonald and N. F. Ness, J. Geophys. Res. **98**, 1, (1993).

[34] M. S. Potgieter *et al.*, Astrophys. J. **403**, 760 (1993).

[35] M. S. Potgieter, Adv. Space Res. **19**, 883 (1997).

[36] J. A., le Roux and H. Fichtner, J. Geophys. Res. **104**, 4709 (1999).

[37] G. P. Zank and H-R. Müller, J. Geophys. Res. **108**, 7, (2003).

[38] H. Cane, *et al*., Geophys. Res. Lett. **26**, 565 (1999).

[39] D. C. Ndiitwani *et al.,* Annales Geophys. **23**, 1061, (2005).

[40] D. J. McComas *et al.,* Geophys. Res. Lett. **27**, 2437 (2000).

[41] U. W. Langner *et al*., J. Geophys. Res. **111**, 1106 ((2006).

[42] U. W. Langner and M. S. Potgieter, Adv. Space Res. **34**, 144 (2004).

[43] R. Schlickeiser, *Cosmic ray Astrophysics* (Springer, Germany, 2002).

[44] S. E. S Ferreira, M. S. Potgieter and K. Scherer, J. Geophys. Res. **112**, A11101 (2007).

[45] K. Scherer *et al*., Astrophysical J. **680**, L105 (2008).

[46] K. Scherer *et al*., Adv. Space Res., **41**, 1171 (2008).

[47] U. W. Langner and M. S. Potgieter, Adv. Space Res. **41**, 368 (2008).

[48] D. McComas and N. Schwadron, Geophys. Res. Lett. **426**, 48 (2006).

[49] N. A. Schwadron, M. A. Lee, and D. J. McComas, Astrophys. J. **675**, 1584 (2008).

[50] H. J. Fahr *et al.,* Astron. & Astrophys., 486, 1 (2008).

[51] M. S. Potgieter, Adv. Space Res. **41**, 245 (2008).

[52] U. W. Langner, M. S. Potgieter and W. R. Webber, J. Geophys. Res. **108**, 8039 (2003).

[53] U. W. Langner and M. S. Potgieter, Astrophys. J. **630**, 1114 (2005).

[54] D. McComas *et al*., 3rd IGPP Conference, AIPC **719**, 162 (2004).

[55] M. Casolino *et al.,* Adv. Space Res. **42**, 455 (2008).

[56] W. R. Webber *et al.,* Geophys. Res. Let. **34**, L20107 (2007).