A&A 442, L11–L14 (2005)
DOI: 10.1051/0004-6361:200500178


Astronomy & Astrophysics

Letter to the Editor

# The heliomagnetic and solar-cycle related variations of the cosmic ray flux modeled with the BoPo-hybrid code

K. Scherer[1,2] and S. E. S. Ferreira[3]

[1] Institut für Astrophysik und Extraterrestrische Forschung, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
e-mail: kls@tp4.rub.de
[2] Now at: Institut für Theoretische Physik, Lehrstuhl IV: Weltraum- und Astrophysik, Ruhr-Universität Bochum, 44780 Bochum, Germany
[3] Unit for Space Physics, School of Physics, North-West University, 2520 Potchefstroom, South Africa
e-mail: fsksesf@puknet.puk.ac.za

Received 27 June 2005 / Accepted 3 September 2005

**ABSTRACT**

Based on the five species hybrid model by Scherer & Ferreira (2005, ASTRA, 1, 17) we describe the observations of energetic cosmic ray particles by the Voyager 1 spacecraft for solar minimum and maximum conditions during both the $A < 0$ as well the $A > 0$ heliomagnetic cycle. Without going into a detailed data and model analysis, we will show that the model (BoPo-code) is well suited to explain the longterm trend in the observed proton data as this spacecraft moves into the outer heliosphere. By comparison of model results to the observations along the Voyager trajectory we predict, depending on cosmic ray energy, a smooth transition in observed radial profiles after the crossing of the termination shock. From a cosmic ray particle perspective the effect of the shock might be seen in the very low energy data (<30 MeV), where a change in radial gradient occurs over the shock. Also, as Voyager 1 moves into the heliosheath, we show that the solar-cycle related changes in cosmic ray observations, which are clearly observed inside the termination shock, are expected to decrease toward the heliopause beyond which the LISM spectra is assumed to be unperturbed.

**Key words.** heliosphere – interstellar medium – cosmic rays

## 1. Motivation

In the past years a lot of effort was put in the development of highly advanced models describing the interaction between the interstellar medium and the solar wind: hydrodynamic models (see e.g. Zank 1999, for a review), 3-D hydrodynamic (e.g. Borrmann & Fichtner 2005), 3-D magneto-hydrodynamic codes (e.g. Ratkiewicz & McKenzie 2003; Pogorelov et al. 2004), 3-D kinetic models (e.g. Izmodenov & Malama 2004), or 2-D dynamic models including energetic particles like galactic cosmic rays (GCRs) and anomalous cosmic rays (ACRs) (e.g. Scherer & Fahr 2003).

On the other hand, the emphasis in modeling the energy-dependent cosmic ray flux (see Potgieter 1998, for a review), was put on kinetic modulation models (e.g. Zhang 2003; Ferreira & Potgieter 2004) solving Parkers transport equation, including also anisotropies (e.g. Jokipii et al. 2004) and acceleration at the termination shock (e.g. Potgieter & Langner 2004). A qualitative description of the changes of the gradients are discussed in Jokipii et al. (1993), where at low energies, the radial gradient changes abruptly from a lower value inside the shock to a higher value outside, where as at high energies, the higher value of the gradient are inside the shock.

Recently, both approaches have been combined by Scherer & Ferreira (2005) using a hybrid code, the so-called BoPo-model: a hydrodynamical model for the interaction between the solar wind and interstellar protons as well as the interaction with the interstellar neutral hydrogen. Due to charge exchange processes in the inner heliosphere between these particle species new ions are created, the pickup ions (PUIs), which are then transported by the solar wind and its magnetic field to the termination shock. This latter species is also described by a hydrodynamic continuity equation. The acceleration of ACRs at the termination shock and their transport as well as that of GCRs into the inner heliosphere is then self-consistently described by a kinetic transport model based on solving the Parker (1965) transport equation in the meridional plane of the heliosphere. Because this is a 2-D axisymmetric model, the description in the ecliptical-crosswind direction is not correct. On the other hand the main modulation of the CRs take place at the nose and over the poles, so that in the meridional plane our model adequately describes the physical situation. The advantage of the 2-D model is that it is fast and one can use it modeling the solar cycle variation dynamically including self-consistently the motion of the termination shock. To our knowledge this is the first time that a complete solar activity cycle can be self-consistently modeled.

In a first step the results from the hydrodynamic part of the code, like plasma velocity, position of the termination shock, the number density of PUIs, etc., are transferred to the kinetic part, where, in a second step, the energy spectra of the ACRs and GCRs are calculated for the entire heliosphere using parameters fully described in Scherer & Ferreira (2005), especially the acceleration from the PUIs to ACRs is taken into account in our model. With the help of these spectra the pressure, e.g. energy density, of the high energetic species is estimated, which then is in a third step, given back into the hydrodynamic part, where it is added as a perturbation to the total hydrodynamic pressure. First results and a more detailed description have been presented by Scherer & Ferreira (2005), including the model of the solar cycle variations of the solar wind parameters.

In this letter we describe the transport of the cosmic ray particles (anomalous and galactic cosmic ray protons) during the solar minimum and maximum conditions, which give the envelopes for the cosmic ray flux. We present the results for $A > 0$ and $A < 0$ solar magnetic cycles, in which the transport of energetic particles differs by their drifts induced by the heliospheric magnetic field. Also solar cycle related changes in the tilt angle of the heliospheric current sheet (which influences particle drifts) and diffusion parameters, due to changes in the heliospheric magnetic field magnitude, are taken into account (see Ferreira & Potgieter 2004, for a full description of the transport parameters). We also compare model results to available data from Voyager 1 at different energies, and show that the data for high energy (>100 MeV) cosmic ray particles are in good agreement with our model, while that of the lower energy range (<30 MeV) differs somewhat, especially in the $A < 0$ cycle. We discuss the latter in more detail below.

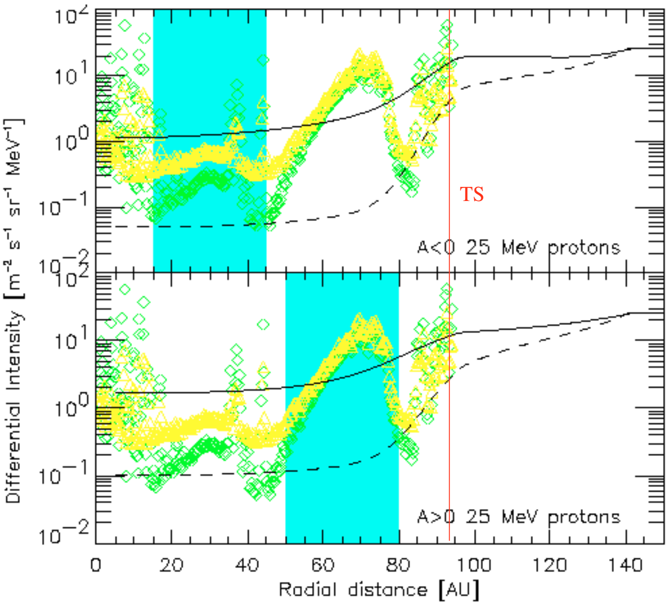


**Fig. 1.** Shown are computed radial profiles for a $A > 0$ cycle in the lower panel and that for the $A < 0$ sub-cycle in the upper panel. Indicated by the shaded regions are the periods in which there were a definite observed polarity and the data can be compared with our model for the $A > 0$ or $A < 0$ cycles respectively, as indicated in the panels. The solid line shows our computation for solar minimum conditions, while the dashed line that for solar maximum. Here the observations in the 18–27 (yellow triangles) and 6–42 MeV (green diamonds) proton chanels are compared to the 25 MeV calculation. On the $x$-axis the heliocentric radial distance is given in AU, while on the $y$-axis the differential intensities are given in m$^{-2}$ s$^{-1}$ sr$^{-1}$ MeV$^{-1}$. The red line indicates the position at which Voyager 1 has crossed the termination shock For more details see text.

## 2. Data versus model

Because we have included a simple Archimedian spiral as the heliospheric magnetic field (a Parker type field (Parker 1963)) modified according to Jokipii & Kóta (1989) to describe its polar extension, there is no continuous transition between an $A < 0$ and an $A > 0$ cycle, and only one polarity of the heliospheric magnetic field can be described at once in the BoPo-code. Therefore, we calculate two models one for each cycle. In both models the heliospheric magnetic field is kinematically continued into the heliosheath assuming that it is still frozen-in in the plasma flow. In Figs. 1 to 3 we have plotted in the upper panels the results for the model of an $A < 0$-cycle and in the lower panel that for an $A > 0$-cycle together with the 26-day averaged data of Voyager 1 spacecraft (available at `http://voycrs.gsfc.nasa.gov/heliopause/heliopause/list26.html`). The details of those data depend strongly on the time-dependent solar wind parameters as well as the position of the heliospheric current sheet. Because a discussion of these details would go far beyond the scope of this letter, we restrict ourselves to the solar minimum and maximum conditions, and, therefore, show only the envelopes for the extreme conditions of a solar cycle, e.g. for the solar minimum (solid lines) and for the solar maximum (dashed lines). We have chosen four energy chanels from the data and compare them with three energies from our model: in Fig. 1, the 18–27 and 6–42 MeV proton chanels compared with the 25 MeV proton calculation, in Fig. 2 the 133–242 MeV proton chanels with that of 180 MeV calculation, and in Fig. 1 the >70 MeV count rates with that of the 2.5 GeV calculation. Unfortunately, we do not know what the fraction of ACRs in the energy range between 18–27 MeV and 6–42 MeV data are, because otherwise we could adjust the injection efficency in our model to fit the measured spectra. Thus, we assumed a injection efficiency of 20%, i.e. this fraction of pickup ions is converted into ACRs at the termination shock.

In the figures only model results for extreme solar minimum and maximum solutions are shown, therefore the data should lie in between the modeled envelopes. As obvious from in all three figures, there is, in that respect, a very good agreement between the computations and the observations except for the very low energy range and for solar minimum conditions in the $A > 0$ polarity cycle. For this period, where the Voyager 1 spacecraft was close to the termination shock, the observed differential fluxes are higher as our computed ones. The explanation of this effect is that we have probably a too high perpendicular diffusion coefficient $\kappa_\perp$ in the polar direction resulting in too small computed latitudinal gradients. Also we model a minimum tilt angle of 15 degrees for solar minimum periods, which might be slightly too high and could be less than 10 degrees. In both cases we would get to smaller differential fluxes

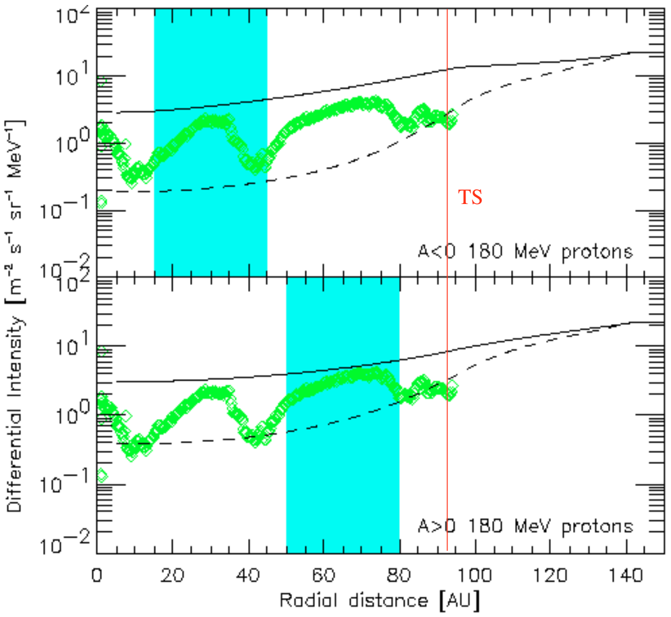


**Fig. 2.** Same as in Fig. 1 but for the measurements in 133–242 MeV proton chanel compared to our model calculation of 180 MeV. Here the data and the model are in good agreement.

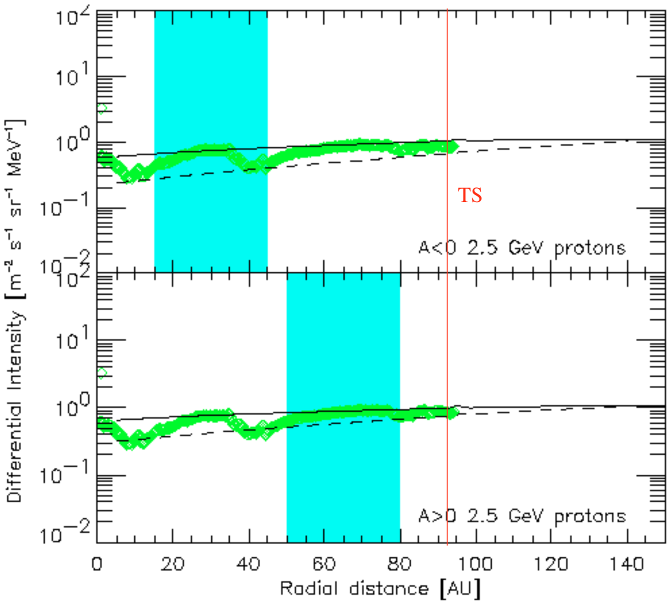


**Fig. 3.** Same as in Fig. 1 but for the >70 MeV count rates which are compared to our model calculation of 2.5 GeV. The data and the model are also in good agreement. Note, for easy comparison the same scale is used in all three figures.

and, therefore, we will improved on that in a forthcoming parameter study.

Anyhow, all the model curves for the solar minimum and maximum conditions in Figs. 1 to 3 show a much smaller variation due to solar activity after the passage of the termination shock which depends on latitude, and varies between 90 AU and 93 AU along the Voyager 1 trajectory in our model because of the solar cycle variations in the solar wind speed and density. Also shown in these figures is that the solar minimum and maximum curves become identically at the heliopause, after which, due to the boundary conditions of our model, the interstellar spectrum is undisturbed. Shown here is that future data from Voyager 1, in particular the measured modulation amplitude between solar minimum and maximum as it moves further into the heliosheath, may play an important role in determining the location of the heliopause.

In all three figures shown, our model predicts a gradual increase in the computed proton intensities from the termination shock towards the heliopause, and less difference between the two $A \lessgtr 0$ cycles. Such a behavior was recently presented Decker et al. (by 2005) for the Low Energy Charged Particle (LECP) Experiment: after reaching a boundary, most probably the termination shock, the fluxes of the low energy particles became much smoother and slowly increase towards the heliopause. Because in the dynamical models the memory of the heliosphere (Scherer & Fahr 2003; Zank & Müller 2003) plays an important role, it is not easy to distinguish between spatial and temporal effects, because the information of previous solar cycles is stored in the heliosheath and smeared out in time. Moreover, because Voyager 1 is the only spacecraft in the heliosheath it is also not easy to distinguish between spatial and temporal effects. Therefore, we refer to a spatial increase of the CR fluxes towards heliopause, because any temporal information is smoothed and may finally not be observable in the heliosheath. But more detailed analysis of the dynamic models will be done in future.

We have not included the low energy range (<10 MeV) into our presentation, because we are still in a test phase modeling the low energy part of the ACRs, which is physically identical to the energies of strongly accelerated PUIs. Also evident in these figures is that only the cosmic ray particles in the 25 MeV range show signatures of a shock crossing where the computed radial gradient changes across the shock. According to the announcement at the Solar Wind 11 conference, in Whistler, Canada, 2005, Voyager 1 has now crossed the termination shock also from a cosmic ray perspective Kerr (2005). As future data will become available we expect a definite change in radial gradient.

A similar model calculating cosmic ray transport in a 3D heliosphere, but without drifts was presented Florinski et al. (2003). They showed also results mainly in the meridional plane, which are quite similar to our 2D-model including simulated drifts. Both models calculate CR transport as a function of energy, directly from the LISM. Both models also showed that CR transport in the inner heliosphere is not sensitive to the nose-tail asymmetry of the heliosphere, but the Florinski et al. (2003) model did not include dynamic effects, as where presented in this letter using the dynamical BoPo-code, see also Scherer & Ferreira (2005). The dynamical changes are important to CR's to describe temporal effects like solar cycle induced variations in the tilt angle as well as in drifts, and, moreover to model the time dependence in the distribution coefficients.

## 3. Conclusions and outlook

We have shown, that the BoPo-hybrid code can explain the cosmic ray flux band in the high energy range quite satisfactory. While in the lower energy range deviations between the data and the model exists, which can be improved by a different choice of our parameters, without strongly affecting the high energetic particles, like the perpendicular diffusion coefficient $\kappa_\perp$. A more detailed discussion can be found in Scherer & Ferreira (2005) and some new aspects will be discussed in a forthcoming paper Ferreira & Scherer (2005).

Nevertheless, our model predicts a gradual increase in cosmic ray intensities toward the heliopause beyond the termination shock as seems be observed with the LECP on board Voyager 1 (see reference to web page above). Also as Voyager 1 moves into the heliosheath the modulation amplitude over a solar cycle gradually decreases and might play an important role in the estimation of the location of the heliopause. As shown, signatures of the termination shock can only be seen in the low-energy (<30 MeV) computations where the radial gradient changes across the shock due to intensity enhancements from particles being accelerated at this shock. Future data from Voyager 1 at these low energies, and the modeling will, therefore, play an important role to establish whether a change in radial gradient was observed indicating a shock crossing.

In the future we will improve the BoPo-hybrid code to go continuously from one cycle to the other. Then it will be possible to explain the data in more detail, especially the transition periods from one polarity cycle to another during extreme solar maximum conditions.

*Acknowledgements.* We whish the thank Marius Potgieter, Hans Fahr, Horst Fichtner and Bernd Heber for valuable discussions. The authors are also grateful for financial support granted to them by the Deutsche Forschungsgemeinschaft in the frame of the project "Heliotrigger" (Fa 97/28-1) and "Heliocauses" (FI706/6-1) as well as from the South African National Research Foundation under grant number 2053475. This manuscript is also part of the ISSI workshop on "The dynamic heliosphere, variable cosmic environments and their imprints in Earth's archives".

## References

Borrmann, T., & Fichtner, F. 2005, Adv. Space Res., in press
Decker, R. B., Krimigis, S. M., & Roelof, E. C. 2005, Geophys. Res. Abstr., 7, 08874, SRef-ID: 1607-7962/gra/EGU05-A-08874
Ferreira, S. E. S., & Potgieter, M. S. 2004, ApJ, 603, 744
Ferreira, S. E. S., & Scherer, K. 2005, ApJ, submitted
Florinski, V., Zank, G. P., & Pogorelov, N. V. 2003, J. Geophys. Res., 108, 1, doi:10.1029/2002JA009695
Jokipii, J. R., & Kóta, J. 1989, Geophys. Res. Lett., 16, 1
Jokipii, J. R., Kóta, J., & Merenyi, E. 1993, ApJ, 405, 782
Izmodenov, V., & Malama, Y. G. 2004, AdSpR, 34, 74
Jokipii, J. R., Giacalone, J., & Kóta, J. 2004, ApJ, 611, L141
Kerr, R. A. 2005, Science, 308, 1237
Parker, E. N. 1963, Interplanetary dynamical processes (New York: Interscience Publishers)
Parker, E. N. 1965, Planet. Space Sci., 13, 9
Pogorelov, N. V., Zank, G. P., & Ogino, T. 2004, ApJ, 614, 1007
Potgieter, M. S. 1998, Space Sci. Rev., 83, 147
Potgieter, M. S., & Langner, U. W. 2004, ApJ, 602, 993
Ratkiewicz, R., & McKenzie, J. F. 2003, J. Geophys. Res., DOI: 10.1029/2002JA009560
Scherer, K., & Fahr, H.-J. 2003, Ann. Geophys., 21, 1303
Scherer, K., & Ferreira, S. E. S. 2005, ASTRA, 1, 17
Zank, G. P. 1999, Space Sci. Rev., 89, 413
Zank, G. P., & Müller, H.-R. 2003, J. Geophys. Res., DOI: 10.1029/20002JA009689
Zhang, M. 2003, Adv. Space Res. 32, 603