Charge-dependent solar modulation in light of the recent PAMELA data

Henning Gast* **and Stefan Schael***

* *I. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany*

***Abstract*. The PAMELA collaboration has recently published data on the cosmic-ray positron fraction, confirming indications of an unexpected rise towards higher energies seen by earlier experiments. At the same time however, the low-energy data deviate significantly from the earlier measurements (e.g. CAPRICE, HEAT, and AMS-01).**

In order to investigate this observation, a simple model of charge-dependent solar modulation is presented that is based on the well-known force-field approximation. A single parameter is added, and the predictions of the well-established Galprop model for interstellar cosmic-ray propagation are used for the local interstellar fluxes of protons, antiprotons, positrons and electrons. It is shown that the low-energy spectra of these species that were measured in recent years by AMS-01, BESS, PAMELA and others are then all described by the conventional Galprop propagation model with very good precision. In particular, the positron fraction measured by PAMELA is found to be in excellent agreement with earlier measurements over the entire energy range if charge-dependent solar modulation effects are taken into account.

***Keywords*: solar modulation, positron fraction, PAMELA experiment**

I. Introduction

The flux of cosmic-ray positrons has long been considered as a probe for new phenomena [1]. As no primary source for cosmic-ray positrons is known, the mechanism of secondary production in connection with interactions of cosmic-ray protons and nuclei with interstellar matter predicts a gradual decline of the positron fraction, i.e. the flux ratio $e^+/(e^+ + e^-)$, with energy. Earlier indications of an unexpected rise towards higher energies, seen by HEAT [2] and AMS-01 [3], [4] have recently been confirmed by measurements of the PAMELA experiment [5] with high statistical accuracy and improved energy range (fig. 1). A surge of publication activity has ensued aiming at an explanation of the excess [6]. The sources proposed range from nearby pulsars to the annihilation of exotic dark matter particles. However, it is frequently overlooked that the low-energy positron fraction data measured by PAMELA are in disagreement with earlier measurements, too, which raises the question if the entire measurement is plagued by some systematic problem. Here, we show that the low-energy data can be reconciled with the older results by allowing for charge-sign dependent solar modulation effects that can be modelled by a simple extension of the frequently used force-field approximation. After a very brief review of this model in section II, section III deals with charge-sign dependent solar modulation effects in light of the PAMELA data.

II. Solar modulation in the force-field approximation

Arriving at the outskirts of the solar system, the fluxes of cosmic-ray particles are modulated due to interactions with the solar wind [8]. The first hints at this effect came from observations of an anticorrelation between neutron monitor counts and the sunspot number, the latter being an indicator of the level of solar activity [9]. The solar wind originates from the corona of the Sun. A magnetic field, rooted in the Sun, is frozen into the solar wind plasma, and the Sun's rotation leads to the creation of the large-scale structure known as the Archimedes spiral. Cosmic-ray particles are scattered on the magnetic fields. Gleeson and Axford [10] model the solar modulation by taking into account cosmic-ray diffusion through this magnetic field, convection by the outward motion of the solar wind, and adiabatic deceleration of the cosmic rays in this flow [11]. In the force-field approximation, the effect of solar modulation can be described by a single parameter ϕ that depends on the solar wind speed V and the diffusion coefficient κ. The interstellar cosmic-ray flux J_{IS} is then modulated to yield the locally observed one J as

$$J(E) = \frac{E^2 - m^2}{(E + |z|\phi)^2 - m^2} \cdot J_{IS}(E + |z|\phi) \qquad (1)$$

where z is the particle charge. The modulation parameter ϕ has the dimension of a rigidity and is of the order of $500\,\mathrm{MV}$ but it changes with time in accordance with the solar cycle. It must be stressed that the modulation parameter is not a model-independent quantity. Because the interstellar flux J_{IS} appears in (1), a value of ϕ can only be quoted in the context of a given propagation model. For the purposes of this study, we have used the predictions of the well-established Galprop code, specifically the conventional model outlined in [12], both for the primary proton and electron spectra and for the secondary fluxes of positrons and antiprotons.

III. Charge-sign dependent solar modulation effects in light of the PAMELA data

At first glance, the positron fraction measured by PAMELA at low energies, below $10\,\mathrm{GeV}$, seems

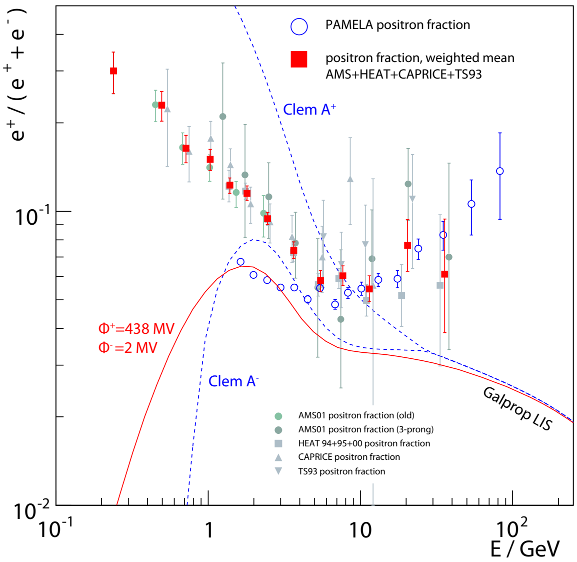

Fig. 1. Positron fraction data compared to predictions for the low-energy behaviour, based on the local interstellar spectrum (LIS) obtained in the conventional Galprop model. Data are from PAMELA [5], AMS-01 [3], [4], HEAT [2], CAPRICE [13] and TS-93 [14]. The weighted mean of the earlier measurements, taken during comparable solar conditions, is included for clarity. The solid line is based on charge-sign dependent modulation parameters in the force-field approximation formula (1), the dashed lines are obtained in the empirical model of Clem et al. [15], as described in the text.

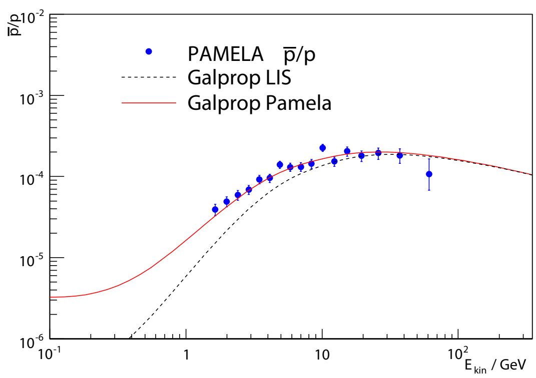

Fig. 2. Antiproton-to-proton ratio measured by PAMELA [17] compared to the prediction obtained by applying the same charge-sign dependent solar modulation to the local interstellar spectra (LIS) predicted by the propagation model as to the positron fraction.

puzzling. While the other measurements taken in recent years agree well in this energy range, the PAMELA data points indicate significantly fewer positrons (fig. 1). If the pronounced rise at high energies apparent in the PAMELA data is to be taken seriously, it must first be shown that this observation does not point to a systematic error in the response of the PAMELA apparatus nor the data analysis. In this section, it is argued that charge-sign dependent solar modulation [15], [16] is a possible way to explain all measurements quoted above.

The amplitude of solar modulation varies along with the solar cycle, with its well known half-period of eleven years. A good measure for the activity of the sun is the sunspot number, which has been observed almost continuously for the last centuries. Although the magnetic field of the sun is complex, it is nearly always dominated by the dipole term. The projection of this dipole on the solar rotation axis can be either positive or negative and these two states are referred to as A^+ and A^-, respectively. The dipole reverses direction at each sunspot maximum, leading to alternating magnetic polarity in successive solar cycles [18], [19], [20].

It can be expected that solar modulation depends on the charge sign of a particle, affecting positrons and electrons differently. As a simple extension of the force-field approximation used so far, it can be assumed that the modulation parameter ϕ in (1) is charge-dependent and takes different values ϕ^+ and ϕ^- for positively and negatively charged particles, respectively. This phenomenological approach is justified by the ability to describe different data sets as shown below and by its simplicity.

Allowing for different values of ϕ^+ and ϕ^-, a fit of the local interstellar positron fraction calculated in the conventional Galprop model to the PAMELA positron fraction data below $4\,\mathrm{GeV}$ yields values of $\phi^+ = 438\,\mathrm{MV}$ and $\phi^- = 2\,\mathrm{MV}$ with statistical uncertainties of $4\,\mathrm{MV}$ (fig. 1). These values mean that electrons can reach the Earth almost unhindered by the solar wind while positrons are moderately suppressed so that the fraction of positrons is reduced with respect to the charge-symmetric case.
In their empirical model of charge-dependent solar modulation, Clem et al. [15] assumed that the flux J_E of a given species with charge sign q measured at Earth is related to the interstellar flux J_{IS} by

$$J_E(R, \hat{\phi}, qA) = C(qA, R) \cdot M(R, \hat{\phi}) \cdot J_{IS}(R) \quad (2)$$

where R is rigidity, A is the solar magnetic polarity, and $\hat{\phi}$ is the phase of the solar cycle. C and M are two modulation factors, and $\hat{\phi}$ is associated to the modulation parameter considered before. This simple model neglects the adiabatic deceleration present in (1), but it has the advantage that J_E can be expressed in terms of just J_{IS} and $\varrho(R)$, the ratio of the total electron fluxes in the A^+-cycle to the total electron fluxes in the A^--cycle. The empirical data on $\varrho(R)$ as assembled by Clem et al. can be parameterised as

$$\varrho(R) = 0.166 \log(R/\mathrm{GeV}) + 0.452 \quad (3)$$

It can then be shown that the positron fraction F_E at Earth is related to the interstellar one F_{IS} by

$$F_E = \frac{F_{IS}^2(\varrho + 1) - \varrho F_{IS}}{2F_{IS} - 1} \qquad \text{for } A^- \quad (4)$$

and

$$F_E = \frac{F_{IS}^2(\varrho + 1) - F_{IS}}{\varrho(2F_{IS} - 1)} \qquad \text{for } A^+ \quad (5)$$

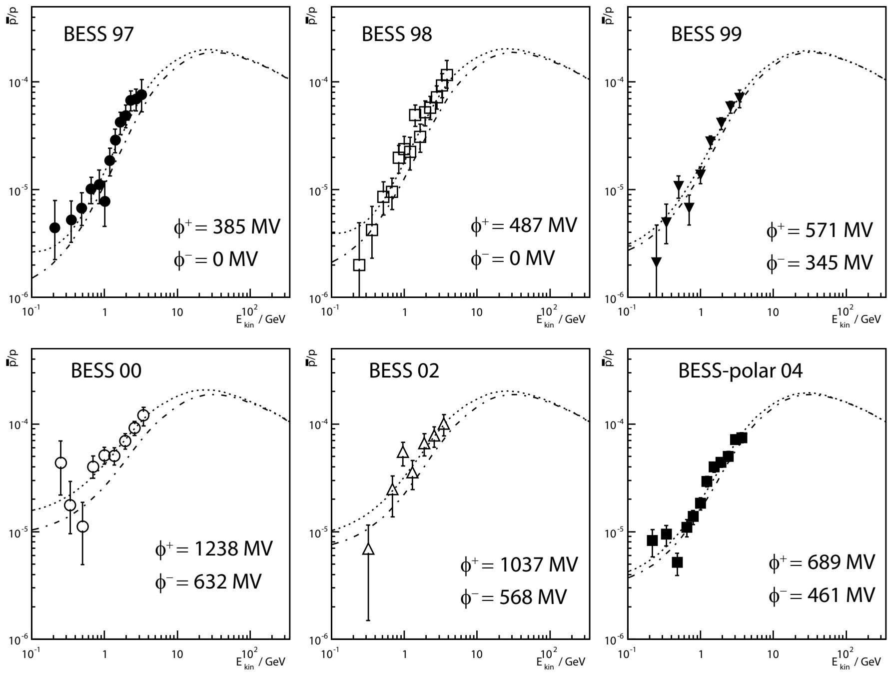

Fig. 3. $\bar{p}/p$-ratio as measured by BESS [21], [22], [23], [24], [25], compared to the prediction in the conventional Galprop model. The dash-dotted line is found for the case of charge-symmetric solar modulation, using the modulation parameter ϕ obtained from a fit to the corresponding proton spectra. Allowing different values of ϕ^+ and ϕ^- yields the dashed lines. The best-fit values are given in the figure.

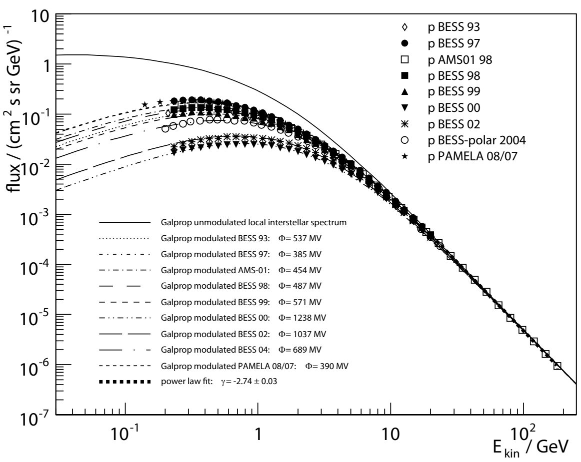

Fig. 4. Cosmic-ray proton spectrum as measured by BESS [26], [27], AMS-01 [28] and PAMELA [29], together with the prediction by the Galprop conventional model. The effect of solar modulation in the data is clearly seen. The unmodulated model flux is plotted, as well as the modulated ones, using the best-fit modulation parameter ϕ for each data set.

The resulting curves are included in fig. 1. It can be seen that the trend predicted for the A^- cycle, during which the PAMELA data were taken, is rather similar to the curve predicted in the $\phi^\pm$-model presented above.

The antiproton-to-proton ratios measured by PAMELA and BESS can be used to cross-check the $\phi^\pm$-model. In fact, using the same $\phi^\pm$-values as for the positron fraction, the PAMELA $\bar{p}/p$-ratio can be reproduced well (fig. 2). In addition, the $\bar{p}/p$-ratios measured by BESS in a series of flights from 1997 to 2004 are perfectly described by the conventional Galprop model in our model of charge-sign dependent solar modulation (fig. 3). Here, the value of ϕ^+ was extracted from a fit to the corresponding proton spectra (fig. 4) and ϕ^- was then the only remaining parameter in a fit of the $\bar{p}/p$-ratio.

Looking at the correlation of the solar activity, expressed in terms of the sunspot number, with the modulation potential obtained from fits to the proton spectra taken in recent years, a good match is found in general (fig. 5). The value for the PAMELA protons is somewhat higher than expected from the trend implied by the solar data, by a margin comparable to the difference in the values of ϕ^+ and ϕ^- quoted above. In fact, the antiproton curve seems to be lagging behind the proton curve during the last A^+-cycle, while it matches the sunspot curve well for the current A^--cycle, with the proton curve running ahead. There is some tension in the model, however: The value found for ϕ^- from the antiproton data is consistent with zero for certain periods, and there is a discrepancy between the AMS-01 electron data and the BESS $\bar{p}$ data in 1998.

A prediction of this model of charge-dependent solar modulation is an unexpected and rather drastic decrease of the positron fraction at the lowest energies, below 1 GeV (fig. 1). A new measurement at these

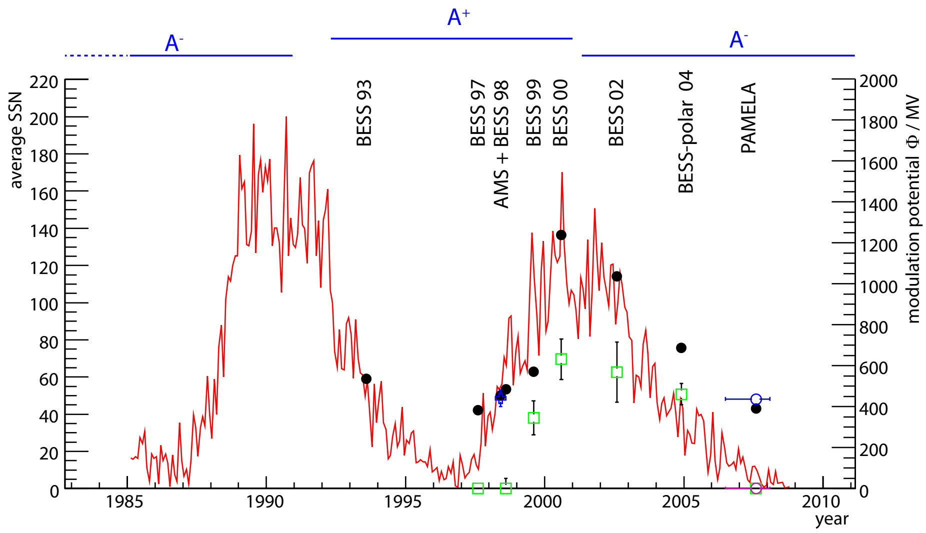

Fig. 5. Monthly average of the observed sunspot numbers [30] since 1985, compared to the values of ϕ^+ (full circles) extracted from the fits to the proton spectra included in fig. 4. Values of ϕ^- extracted from the antiproton data are shown as open squares. The charge-sign dependent parameters used to describe the low-energy positron fraction measured by PAMELA (open circles) are depicted, too. The open cross is the value of ϕ^- found to fit the AMS-01 electron data. The cycle of the solar magnetic polarity is indicated by the bars at the top of the figure, with the approximate start and end dates taken from [31] and [32].

energies during the current solar cycle is therefore highly desirable.

Using the model of solar modulation presented in this section and the local interstellar positron and electron spectra calculated in the Galprop conventional model, both the previously published data and the new PAMELA positron fraction data can be corrected for the solar modulation effects to obtain estimates of the interstellar amplitudes (fig. 6). The result shows that in this model, the PAMELA data are in very good agreement with the weighted mean of the data from AMS-01, HEAT, CAPRICE, and TS93.

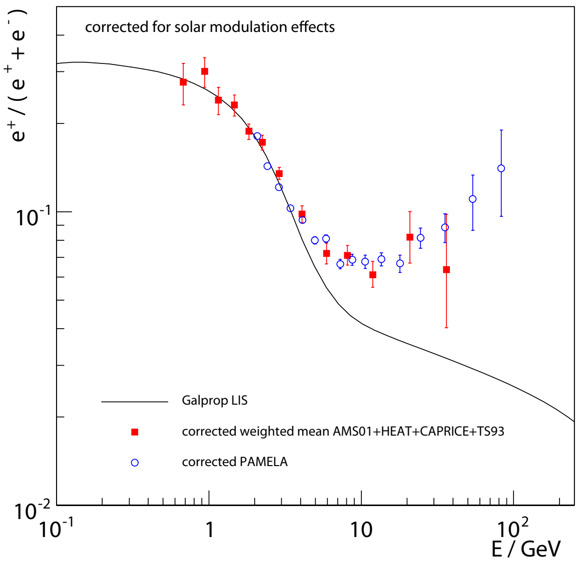

Fig. 6. Positron fraction data corrected for solar modulation effects according to the Galprop conventional model. PAMELA data have been corrected based on the charge-sign dependent model, the weighted mean of the previously published data has been corrected based on a charge-symmetric model using $\phi = 442\,\mathrm{MV}$.

REFERENCES

[1] M. Kamionkowski and M.S. Turner, Phys. Rev. D **43** (1991) 1774-1780
[2] J.J. Beatty et al., Phys. Rev. Lett. **93** (2004) 241102
[3] J. Alcaraz et al., Phys. Lett. B **484** (2000) 10-22
[4] M. Aguilar et al., Phys. Lett. B **646** (2007) 145-154
[5] O. Adriani et al., Nature **458** (2009) 607-609
[6] An extensive list of literature is found in S. Profumo, arXiv:0812.4457v2.
[7] M. Boezio et al., ApJ **561** (2001) 787
[8] M.S. Longair, High Energy Astrophysics, Cambridge University Press, 1992, reprinted with corrections 2004
[9] T. Stanev, High Energy Cosmic Rays, Springer, 2004
[10] L.J. Gleeson and W.I. Axford, ApJ **154** (1968) 1011-1026
[11] E.N. Parker, Planet. Space Sci. **13** (1965) 9-49
[12] V.S. Ptuskin et al., ApJ **642** (2006) 902-916
[13] M. Boezio et al., ApJ **532** (2000) 653-669
[14] R.L. Golden et al., ApJ **457** (1996) L103-L106
[15] J.M. Clem et al., ApJ **464** (1996) 507-515
[16] J.W. Bieber et al., Phys. Rev. Lett. **83** (1999) 674-677
[17] O. Adriani et al., Phys. Rev. Lett. **102** (2009) 051101
[18] H.D. Babcock, ApJ **130** (1959) 364
[19] J.M. Clem et al., J. Geophys. Res. **105** (2000) 23099-23105
[20] J. Clem and P. Evenson, J. Geophys. Res. **109** (2004) A07107
[21] S. Orito et al., Phys. Rev. Lett. **84(6)** (2000) 1078
[22] T. Maeno et al., Astropart. Phys. **16** (2001) 121-128
[23] Y. Asaoka et al., Phys. Rev. Lett. **88(5)** (2002) 051101
[24] S. Haino et al., Proc. 29$^{\text{th}}$ ICRC **3** (2005) 13-16
[25] K. Abe et al., Phys. Lett. B **670** (2008) 103-108
[26] J.Z. Wang et al., ApJ **564** (2002) 244-259
[27] Y. Shikaze et al., Astropart. Phys. **28** (2007) 145-167
[28] J. Alcaraz et al., Phys. Lett. B **490** (2000) 27-35
[29] M. Casolino et al., arXiv:astro-ph/0810.4980v1
[30] Solar Influences Data Analysis Center, `http://sidc.oma.be/sunspot-data/`
[31] H.B. Snodgrass et al., Solar Physics **191** (2000) 1-19
[32] C.J. Durrant and P.R. Wilson, Solar Physics **214** (2003) 23-29