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Solar Modulation of Low-Energy Antiproton and Proton Spectra Measured by BESS

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Abstract: The spectra of low-energy cosmic-ray protons and antiprotons have been measured by BESS in nine high-latitude balloon flights between 1993 and 2004. These measurements span a range of Solar activity from before the previous Solar minimum through Solar maximum and the onset of the present Solar minimum, as well as a Solar magnetic field reversal from positive to negative in 2000. Because protons and antiprotons differ only in charge sign, simultaneous measurements provide a sensitive probe of charge-dependent Solar modulation. The antiproton to proton ratio measured by BESS is consistent with simple spherically symmetric models of Solar modulation during the Sun's positive polarity phase, but requires charge-sign-dependent drift models during the negative phase. The BESS measurements are presented and compared to models of Solar modulation.

Introduction

The Balloon-borne Experiment with a Superconducting Spectrometer (BESS) has carried out ten flights from 1993 to 2004, nine of which were high-latitude flights measuring the flux in the cosmic radiation of antiprotons, protons and helium isotopes, as well as searching for antihelium [1]. While the principal thrust of this work has been the search for antiparticles of significance to cosmology or particle physics, the repeated measurements of proton and antiproton spectra over many years and a range of Solar activities provide a useful set of data for examining Solar modulation of the galactic cosmic radiation. In addition, a close understanding of the effects of Solar modulation is needed to allow scrutiny of the spectrum of the lowest energy antiprotons for any possible deviations from the secondary antiproton spectrum that might be an indicator of an exotic source, e.g. primordial black hole decay or neutralino annihilation [2] [3] [4]. The BESS-

Polar instrument is the third generation version of the BESS detector, consisting of a superconducting solenoidal magnet, a dual time-of-flight system measuring charge and velocity, a gas drift chamber measuring incident particle trajectories and an aerogel Cherenkov detector augmenting rejection of low-mass particles (electrons and muons). BESS-Polar-I, the first flight of the new instrument, was carried out in Antarctica in December 2004. Details of the instrument and flight are found in [5] and [6]. During its 8.5 day flight, BESS-Polar-I collected about four times the number of antiprotons collected by BESS (1995+1997) around the last Solar minimum. In this paper we present the ensemble of proton and antiproton spectra measured by BESS from the last Solar minimum to the 2004 flight, and compare these measurements with expectation from models of Solar modulation.

Measured Proton and Antiproton Spectra

Proton spectra measured by BESS are shown in Figure 1 [7] [8]. The solid curves are obtained by using indicated modulation factors with the force

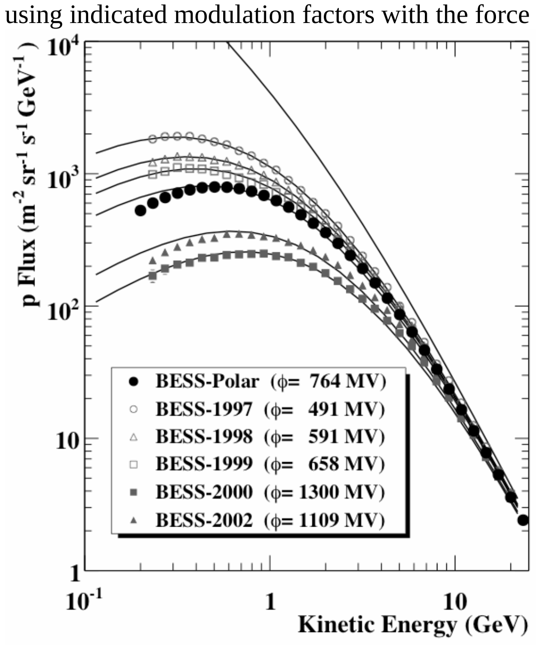

Figure 1: Proton spectra measured by BESS.

field approximation [9] applied to a single assumed local interstellar spectrum (LIS), also shown in Figure 1. Antiproton spectra measured by BESS are shown in Figure 2 [10]. The dash-dot and dashed curves, following the method of [3], are the expected secondary antiproton spectra using the standard leaky box to produce the LIS of secondary antiprotons, and then applying plausible assumptions about the Solar wind and diffusion coefficients in a numerical solution of the spherically symmetric model of Solar modulation [9], using the effective modulation factors of 550 MV and 841 MV, respectively.

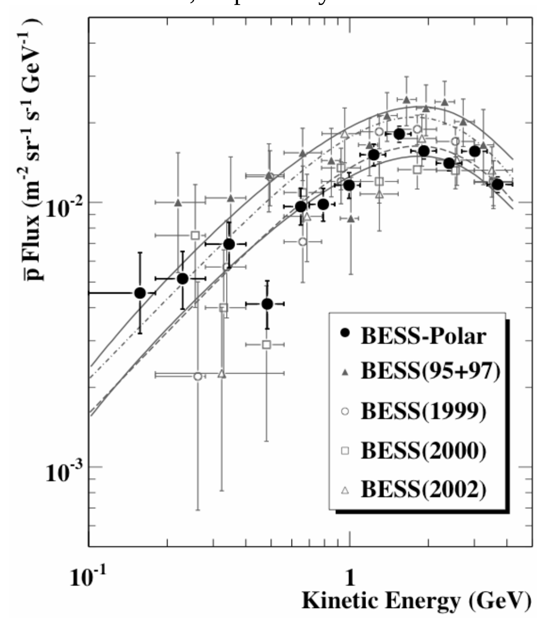

Figure 2: Antiproton spectra measured by BESS.

The upper solid curve in Figure 2 uses the GALPROP code with a diffusion/convection model tuned to the BESS(1995+1997) to produce the antiproton LIS. Solar modulation is carried out with a two-dimensional drift model with a magnetic field (current sheet) tilt angle of 25^{o} [11] [12] [13]. The tilt angle is often used as a proxy for the level of Solar activity, and is related to neutron monitor counts. Similarly, the lower solid curve employs a diffusion/reacceleration model to produce the antiproton LIS and a drift model with a tilt angle of 25^{o} [14]. Several features of Figures 1 and 2 may be observed. As has often been noted, at low energies the variation of the flux produced by Solar modulation is greater for the protons than for the antiprotons. This difference in response to the modulation results from the differing shape of the LIS spectra. In Figure 1, in the few hundred MeV energy range, the proton spectra taken in 2002 and 2004 exhibit small but definite deviations from the model curves produced using the force field approximation. A more sophisticated approach to Solar modulation was suggested by Jokipii and Kopriva [15] who pointed out that particle drifts in the heliospheric magnetic field were important, and that modulation would hence be charge-sign dependent.

Antiproton/Proton Ratio Time Variation

Charge-sign dependence of Solar modulation can most clearly be seen in the flux variation with time of particles with opposite electrical charge but the same mass, i.e. electrons and positrons [16] or antiproton and protons. Figure 3 shows BESS measurements of the antiproton/proton ratio energy dependence in comparison with drift model calculations at various tilt angles.

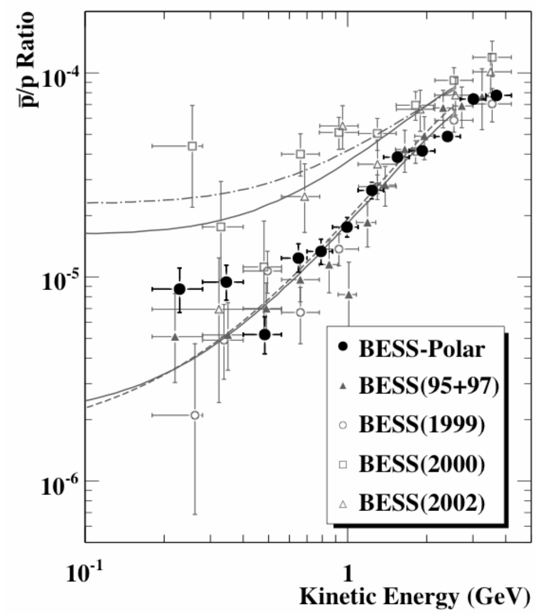

Figure 3: The antiproton/proton ratio measured by BESS. The drift model curves for various tilt angles, from [11], are: dash-dot is A<0, 65°; upper solid is A<0, 25°; dashed is A>0, 65°; bottom solid is A>0, 15°.

In 2000, the Solar magnetic field underwent a polarity reversal, changing from the A>0 state in which the drift of positive cosmic rays is inward toward the magnetic poles to the A<0 state in which the opposite is true. The extreme suppression of the low energy proton spectrum immediately following polarity reversal is seen in Figure 1 and is reflected Figure 3. Noting that the tilt angle in 2000 was about 70°, it is seen that the drift model is in accordance with this charge-sign dependence. See Asaoka et al. [17] who first demonstrated this with the BESS data.

In Figure 4, the variation with time of the measured antiproton/proton ratio at 0.7 GeV is shown, along with the drift model calculations of Moskalenko et al. [11], described above, and Bieber et al. [18]. Using the standard leaky box model, Bieber et al. calculate the LIS antiproton spectrum. This is then modulated using a diffusion tensor incorporating physically-based parallel and perpendicular diffusion coefficients and a drift coefficient.

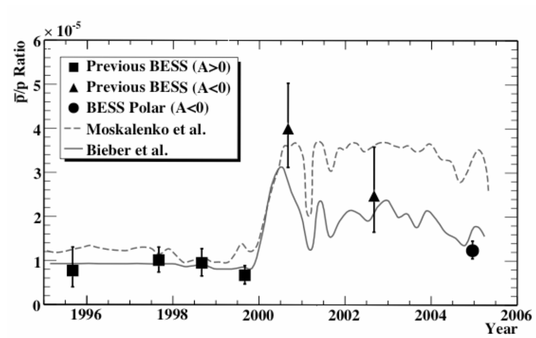

Figure 4: Variation of the antiproton/proton ratio compared with the drift models of Moskalenko et al. [11] and Bieber et al. [18].

For both models, the calculated antiproton/proton ratio as a function of tilt angle has been convolved with data on the tilt angle vs time [13] to produce the curves with detailed structure seen in Figure 4. For both, the predictions for the A>0 epoch before 2000 are a match to the data. Indeed, the spherically symmetric models do well for A>0. Both drift models show a large increase in the antiproton/proton ratio at the transition from A>0 to A<0. However, the model of Bieber is a better fit to the A<0 data, particularly in light of the 2004 BESS-Polar-I point. The physical significance of this is not yet clear. Both models are complex. Data from the anticipated BESS-Polar-II flight in 2007 may help in this regard.

Summary

BESS has simultaneously measured the variations of the fluxes of cosmic-ray protons and antiprotons under a range of Solar conditions from before the previous Solar minimum in the A>0 phase, through Solar maximum and a polarity reversal, and into the A<0 phase approaching Solar minimum, providing a sensitive test of models of the effects of Solar modulation. During the A>0 phase we observe little variation in the antiproton/proton ratio, consistent both with spherically symmetric models of Solar modulation and with charge-sign-dependent drift models. However, immediately following the magnetic field reversal, we observe a large increase in the ratio that is successfully explained by current drift models, but not by the force-field model. Our later measurements in the A<0 phase differentiate between current drift models.

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