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Transient variations in cosmic ray proton fluxes from BESS-Polar I

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Abstract: BESS (Balloon-borne Experiment with a Superconducting Spectrometer) had its first circumpolar flight from Williams Field near McMurdo Station, Antarctica from Dec. 13 to 21, 2004. Our sub-1% precision reveals BESS-Polar I proton fluxes exhibit transient variations at the few1% level. The time progression of proton flux has three main features; a rising flux at the beginning of the flight, a transition region around Dec. 17, followed by quasi-periodic variation. Neutron monitor data show that the BESS-Polar I flight occurred during the recovery phase of a small Forbush decrease. The solar wind plasma and particle data show that this flight took place during the tail end of a high-energy, multiple-eruption solar energetic particle (SEP) event. A high speed solar wind stream arrived near the Earth around Dec. 17, 2004. We present the flux progression as a function of energy between 0.1 - 100.0 GeV and suggest possible physical interpretations.

Keywords: BESS-Polar I, short-term variations, proton fluxes, CIR, turbulent interaction regions, diurnal variations.

1 Introduction

BESS is a US-Japanese collaborative program and has had 11 successful flights since 1993. The main goals of BESS include searches for cosmological antimatter, precise measurements of spectra of light elements in galactic cosmic rays (GCRs or CRs), mainly hydrogen, helium and their isotopes, measurements of atmospheric muons, and study of effects of transients on the cosmic ray intensities. More details can be found in [1, 2] and references therein.

Study of transients is a new field for BESS and has been made possible by the BESS-Polar flights, which provided long enough observations to study transient variations. BESS-Polar I recorded 0.9 x 10^9 events during its 8.5 day flight. A large geometrical acceptance (0.3 m^2 sr) and a large energy range (0.1- a few hundred GeV) make BESS unique for this study. This paper presents the time progression of proton fluxes from BESS-Polar I, compares the proton fluxes with the neutron monitor data, and suggests physical interpretations of the observed variations based on comparisons with the characteristics of the solar wind in the near-Earth space regions.

2 Time progression of proton flux

To carry out the analysis, flux at the top of the instrument was determined for each 4-hour interval. The average atmospheric overburden for that time window was used to apply atmospheric corrections to calculate the flux at the top of the atmosphere. Figure 1 shows the atmospheric overburden during BESS-Polar I. The energy range 0.1 - 100 GeV was then divided into 7 intervals, selected to provide similar statistics giving an average statistical error $<$ 0.3 % in all intervals. The fluxes for each energy interval are plotted as a function of time (figure 2). Details of the analysis procedures can be found in [3]. Preliminary analyses have been given by Hams et al. [4] and Orito et al. [5].

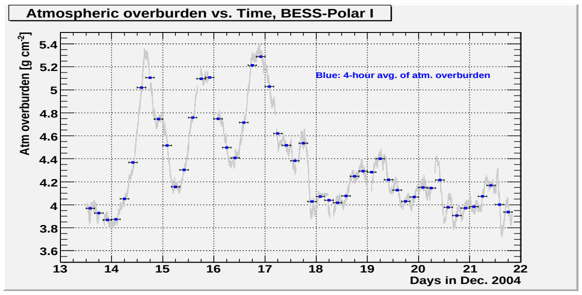


Figure 1: Atmospheric overburden during BESS-Polar I, the dots represent average depth for 4-hour windows used.

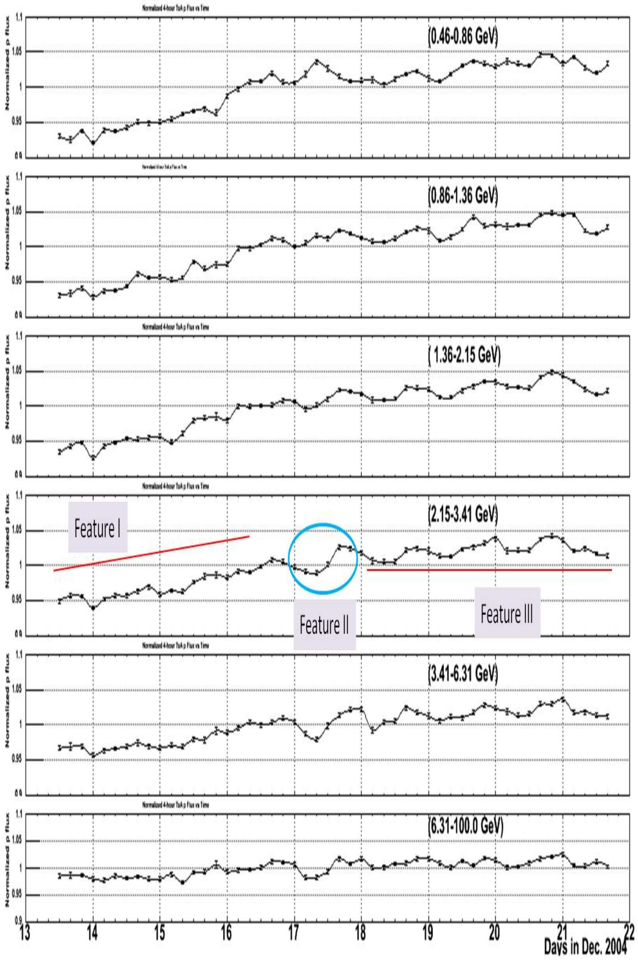


Figure 2: Time progression of normalized BESS proton flux. The vertical axis ranges from 0.9-1.1 for all panels.

2.1 The main features of observed variations

The three main features (figure 2) of the time progression of proton fluxes are:

Feature I: an overall rise in flux for the first few days of the flight consistent with the flight occurring during the recovery phase of a cosmic ray decrease. This is true for all energy intervals. For the lowest energy intervals (up to ∼ 0.86 GeV) the flux increases by (∼ 8-9%) and by ∼ 3% for the highest energy interval (6.31 - 100.0 GeV).

Feature II: a "transition region" between Dec. 17 and 18. A dip is present for energies above ∼ 1.0 GeV and its amplitude increases with increasing energy. For the highest energy interval (6.31 - 100 GeV), this dip is ∼ 3% decrease. At the corresponding time the fluxes at lowest energies have a peak.

Feature III: a quasi-periodic flux after Dec. 17 - 18. At lower energies this periodic behavior is more erratic and has higher amplitudes than those at higher energies. This oscillating behavior appears to be somewhat like diurnal variations. The flux is still recovering/rising with a slower rate at the highest energies.

3 Comparison with other experiments

Next we compared the observed proton flux variations and features with neutron monitor data ([6],[7]). Similar flux variations are seen. Solar wind and interplanetary magnetic field (IMF, denoted as B here) parameters, mainly from ACE [8], are used as complementary dataset to understand the physics of observed variations.

3.1 Comparison with neutron monitor data

Neutron monitor count rates exhibit a decrease during Dec. 13-14, an increase from Dec. 14-17 (Feature I in BESS proton flux), a stabilizing, quasi-periodic behavior from around Dec. 17-21 (Feature III in BESS proton flux). The neutron monitors do not show a "transition region" observed in BESS data but have an onset of periodic flux around this time.

Figure 3 compares BESS proton flux with the count rates from the South Pole neutron monitor. The count rates were normalized by the Dec. 18 count rates (because it is in the middle of the BESS-Polar I flight and this is when the fluxes start to stabilize) and then averaged for the same 4-hour time windows used in our analysis (Figure 2). The

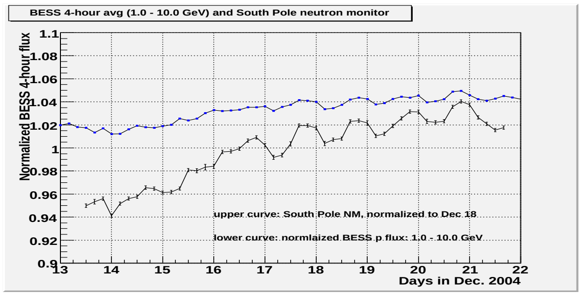


Figure 3: BESS normalized proton flux (1.0 - 10.0 GeV) (lower curve) and normalized South Pole neutron monitor count rates (upper curve). Each point corresponds to a 4-hour time window.

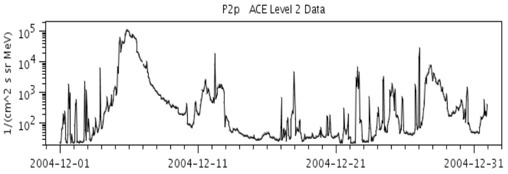
similarity of the neutron monitor measurements reinforce our confidence that the variations observed by BESS-Polar I are real.

3.2 Comparison with solar wind data

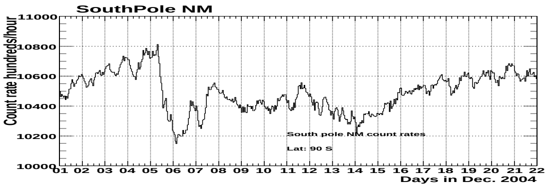
ACE observed a higher speed of solar wind on Dec. 11 - 12, prior to the launch of BESS-Polar I. The speed remained more or less stable from Dec. 13 - 16. Another high speed stream arrived around Dec. 16 - 17; the Earth stayed in this stream till Dec. 19. The magnitude of the IMF was increased around Dec. 12, and again around Dec. 16 - 18. The solar wind proton temperature showed variations at the corresponding times.

3.3 Solar energetic particle (SEP) event

ACE observed a high energy multiple eruption SEP event, which started around Dec. 3 (peaked around Dec. 5), 2004 [9]. BESS-Polar I was launched at the tail end of this event. Another set of increases in the intensity was observed by ACE around Dec. 12-13, which corresponds in time with the small decreases in cosmic ray intensity seen by neutron monitors that occurred until Dec. 14, 2004. The count rates from the South Pole neutron monitor show a decreased intensity around Dec. 5 (start of the SEP, figure 4). Then the cosmic rays started to recover but around Dec. 12-13 there was another decrease corresponding in time to the small SEP flux increase. After this the cosmic rays started another recovery, during which BESS was launched. So the physical process associated with BESS observations appear to be related to this SEP event.



(a) SEP event observed by ACE/EPAM.



(b) South Pole neutron monitor count rates.

Figure 4: Comparison of South Pole neutron monitor count rates with the SEP event observed at ACE [8], [6].

SEPs, which generally contain particles of much lower energies than BESS can observe, can modify the IMF, cause heating, and are sometimes associated with magnetic clouds and merged interaction regions (MIRs). Magnetic clouds and merged interaction regions have been observed to cause transient variations in GCRs [10], [11].

4 Suggested physical interpretations

Due to high speed solar wind stream following a low speed solar wind stream before and during the BESS-Polar I flight, corotating interaction regions (CIRs) and turbulent interaction regions probably affected the observed fluxes. The SEP event led to an investigation for a magnetic cloud. Some physical interpretations are proposed for the observed features in the BESS-Polar I proton flux.

4.1 Feature I: rising flux at the beginning of the flight

Figure 5 panels (1), and (2) show rotation in Bz and decrease in proton temperature ($\sim$0.25 x 10^5 K as compared to $\sim$1.2 x 10^5 K) respectively. Panel (3) shows increased B magnitude. These are the characteristics of a magnetic cloud [12]. Panel (4) shows an increase in solar wind speed and the increase in the proton temperature around Dec. 12; this along with a sharp decrease in the proton density (panel 5) shows a CIR interface around Dec. 12 [11]. Hence, we can suggest that a CIR or a magnetic cloud or a combination of both of these structures may have been responsible for the CR decrease (a small Forbush decrease) of around Dec. 12 - 13. As structures passed, cosmic ray fluxes started to recover; this recovery is seen as Feature I in BESS data.

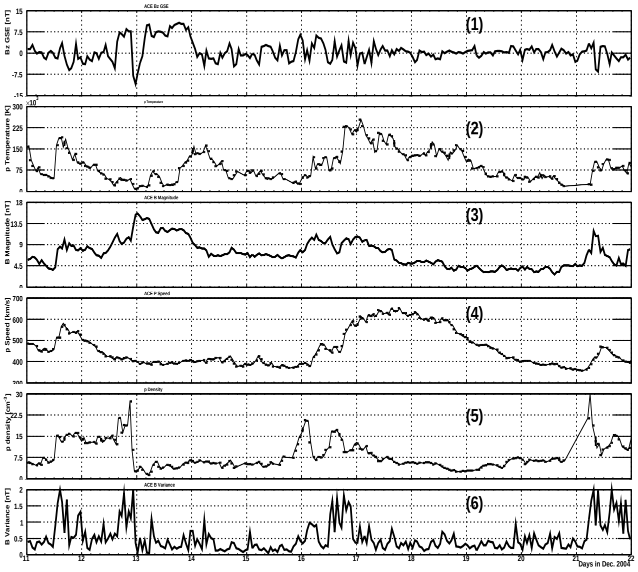


Figure 5: Solar wind parameters during BESS-Polar I. (1) Bz, (2) p temperature, (3) $|B|$, (4) solar wind speed, (5) p density, (6) variance in B.

4.2 Feature II: the "transition region" around Dec. 17

A slow solar wind ($\sim$ 375 - 400 km/s) was followed by a fast solar wind ($\sim$ 650 km/s) around Dec. 16 - 17 near

Earth. During this whole period the components of IMF show enhanced fluctuations indicating the passage of a trapping region.

Around Dec. 17th both B magnitude and turbulence in B (seen via the variance in B) are high; this is indicative of an interface between slow and fast solar wind streams and a turbulent interaction region (TIR) [13]. During this period the CR decreased (BESS proton flux has a dip for energies $\sim > 0.87$ GeV) and when the turbulence passed, the CR started to recover although the IMF magnitude and solar wind speed were still high . There is no further decrease in BESS p flux as the variance has decreased and the BESS p flux starts rising again.

The peak in place of this dip for the lowest energies (< 1.0 GeV) may have been caused by the fact that the low energy particles were trapped in the turbulence whereas the higher energy particles are scattered away in the enhanced IMF.

4.3 Feature III: the quasi-periodic flux towards the end of the flight

Some quasi-periodic variations are seen in our data. Beginning on Dec. 17 it becomes larger in amplitude and shows a period close to one day. The similarity between the BESS and the South Pole neutron monitor data is striking. The McMurdo neutron monitor does not show these diurnal variations. The lower energy proton fluxes showed a higher amplitude while the higher energy fluxes had lower amplitude of this variation.

Our flux variations are well correlated with the many lower latitude neutron monitors as well. We note that the plasma plasma conditions in the space near the Earth stabilized after around Dec. 17, leading to a period of quiet geomagnetic activity and making it easier to observe the periodicity. The diurnal variations are due to the motion of the Earth through the isotropic GCRs. We suggest that Feature III is at least partially a Compton-Getting effect with a phase maximum near 18 hours due to the corotation of the solar plasma overtaking the Earth.

5 Summary

We have measured high precision ($<0.3\%$) relative spectra every 4 hour during the BESS-Polar I flight. To our knowledge this is the first direct measurement of variations at such precision by a balloon or satellite experiment at this time scale and over this energy range. We have observed the most rapid changes in flux with broadband spectral information that contains detailed information on how the cosmic ray flux responds to interplanetary plasma conditions. The suggested physical interpretations for the observed features include effects of solar energetic particles, magnetic clouds, corotating interaction regions, and Compton-Getting anisotropy. The observed features in the time progression of BESS proton fluxes may have been caused by a complex combination of processes produced by these plasma structures. We suggest that these sensitive measurements will be useful for testing models of these physical structures.

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