Short-term and diurnal proton flux variation during the BESS-Polar I balloon flight

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***Abstract*. The Balloon-borne Experiment with a Superconducting Spectrometer (BESS) precisely measures the elemental and isotopic composition of the light cosmic-ray component (Z<3) using a large-acceptance magnetic-rigidity spectrometer. The two most recent BESS flights (2004, 2007) were conducted with the BESS-Polar version of the instrument and launched from Antarctica. The extended multi-day observation time and the improved instrumentation of BESS-Polar have enabled us to observe galactic cosmic ray (GCR) flux changes and we plan to correlate these flux changes with short-term, transient phenomena from the sun.**

In this paper we will demonstrate BESS-Polar's capability to observe GCR flux changes during its first flight, conducted Dec 13–22, 2004, in a transient phase prior to solar minimum. Early in that flight a gradual GCR flux decrease occurred, followed by a subsequent gradual GCR flux recovery. Around Dec 16–17, 2004, the GCR flux recovery was softened by the arrival of a high-speed stream in the solar wind. We will present the proton flux as a function of time for several energy bins up to several tens of GeV, including evidence of diurnal variations. Details of the BESS-Polar I proton and helium analysis are reported elsewhere in these proceedings [1].

***Keywords*: galactic cosmic ray, short-term, transient solar modulation, BESS-Polar**

I. Introduction

The primary science objective of the Balloon-borne Experiment with a Superconducting Spectrometer (BESS) is the search for antimatter in the GCR [2]. Since 1993 the BESS program had 11 successful science flights: 9 northern latitude flights and the most recent two were long-duration flights from Antarctica (2004, 2007).

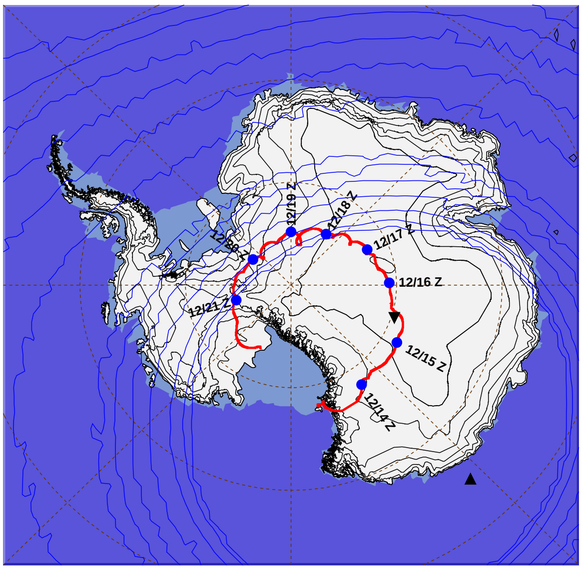

Fig. 1. BESS-Polar I flight trajectory, launched on Dec 13, 2004 and terminated on Dec 21, 2004 after 8.5 days of science observation. The inner isobars represent the geomagnetic cut-off values 0.025, 0.05, 0.01, 0.02 GV.

In addition to the antimatter search [3] [4], BESS has provided high quality proton spectra up to 540 GeV over a wide range of solar activity covering more than a full 11-year solar cycle including the magnetic field reversal in 2000/2001. An effective solar modulation for a given flight can be derived by comparing the measured proton flux with an interstellar proton spectrum. Furthermore, since BESS distinguishes protons from antiprotons, their flux ratio has been used to study the charge-sign dependence of solar modulation [4].

The BESS flights prior to 2004 (pre BESS-Polar) were of approximately one day in duration. The short observation time in the early BESS flights compounded by a charge-biased trigger favoring negatively charged particles, used to retain high sensitivity for the antimatter search, did not provide sufficient event rates to subdivide the data set and study flux changes within the flight. The limitations of short observation times and restrictions due to data acquisition speeds and data storage have been overcome in BESS-Polar. The first (2004) and second (2007/2008) BESS-Polar flight recorded 0.9×10^9 and 4.7×10^9 events during their 8.5 and 24.5 day observations, respectively, without any charge-dependent trigger bias.

The study of in-flight GCR flux variation is a new research opportunity for the BESS program and was partly undertaken to verify the detector efficiency of BESS-Polar during the course of the multi-day flight, but also to study the effects of short-term solar activity on the GCR flux. The BESS-Polar payload is ideally suited for this investigation since it provides a direct measurement of the GCR composition, spectra, and arrival direction. In addition, due to its large geometric acceptance of 0.3 m^2 sr, it allows to derive elemental spectra on time scales that are small compared to the transient solar phenomena. Furthermore, BESS-Polar can observe diurnal variation in the GCR flux reaching Earth, which is caused by the Earth's orbit around the Sun in a co-rotating interplanetary magnetic field.

While other space-based CR experiments can also detect changes in the cosmic ray flux, they mostly operate at much lower energy, whereas BESS-Polar covers the energy range from 0.1–100 GeV for protons. Furthermore, BESS-Polar is unique in its capability to directly measure the diurnal variation. Since most spacecraft are either situated at a lagrangian point or orbit the Earth, they are not sensitive to the diurnal variation. Diurnal variation has mostly been measured by ground-based neutron monitors and muon telescopes. The BESS-Polar experiment offers the first direct measurement of this effect up to several 10 of GeV.

II. BESS-Polar I flight

The BESS-Polar I experiment was launched on Dec 13, 2004 at 05:53 UTC from Williams Field near McMurdo Station in Antarctica. The payload reached float altitude at 11:00 and science observation commenced at 14:00 the same day. For the next 8.5 days BESS-Polar collected continuously data at ~2 kHz recording a total of $\sim 0.9 \times 10^9$ GCR events. The balloon flight was terminated on Dec 21, 2004 at 21:16. The residual atmosphere above the instrument varied between 3.7—5.4 g/cm^2 and the flight average residual atmosphere is 4.33 g/cm^2. The flight trajectory is shown in Fig. 1. From launch until Dec 17, 2004, the payload stayed in the low geomagnetic cut-off region of less that 0.025 GV and for the entire flight stayed mostly below 0.1 GV (see Fig. 1).

The BESS-Polar I flight occurred in a transient phase prior to solar minimum as is illustrated in Fig. 2, exemplified by the Bartol South Pole neutron monitor

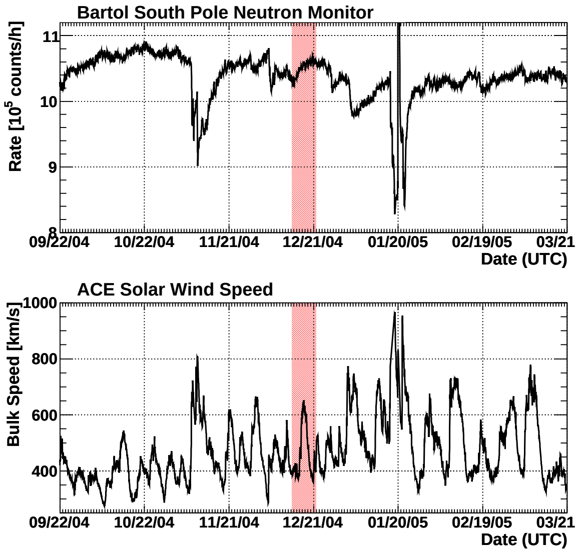

Fig. 2. Solar activity before and after BESS-Polar I flight (highlighted region) exemplified by the Bartol neutron monitor and the solar wind speed from ACE. The BESS-Polar flight occurred in transient phase prior to solar minimum. The flight was proceeded by a strong Forbush decrease in Nov. 2004 and followed by a very large ground level enhancement on 01/20/05.

[5] data and by the solar wind speed recorded by ACE/SWEPAM [6]. The plot is covering a time span of half a year and the time of the BESS-Polar flight is highlighted. As can be seen from Fig. 2, a number of Forbush decreases occurred prior to the BESS-Polar I (Nov 8 & Dec 8 2004). Shortly before the BESS-Polar I launch an interplanetary coronal mass ejection [7] or a Magnetic Could [8] reached Earth and caused a gradual decrease in neutron monitor count rates. Around Dec 14, 2004, the count rate of the neutron monitor started to recover gradually. This GCR flux recovery was softened by a high speed stream in the solar wind reaching Earth around Dec 16–17, 2004. A similar gradual rate decrease and recovery for the same time frame has been observed by the GME G instrument on the IMP-8 spacecraft [9], which is operating at much lower energy.

III. Data Reduction

The study of the short-term flux variation presented here is demonstrated for protons, but we plan to study other GCR components including helium an antiprotons in the future. In the following, we briefly summarize the selection criteria and corrections used to derive the proton flux. The method described is applicable for any time interval, i.e. the entire flight or a 4-hour interval. A detailed discussion of the proton analysis for the BESS-Polar I flight can be found elsewhere in these proceedings [1] and [4].

Identified proton candidates in an observed time interval are corrected for energy losses in the instrument and the residual atmosphere as well as interaction losses in the atmosphere and instrument plus secondary proton production from the spallation of higher charges. The

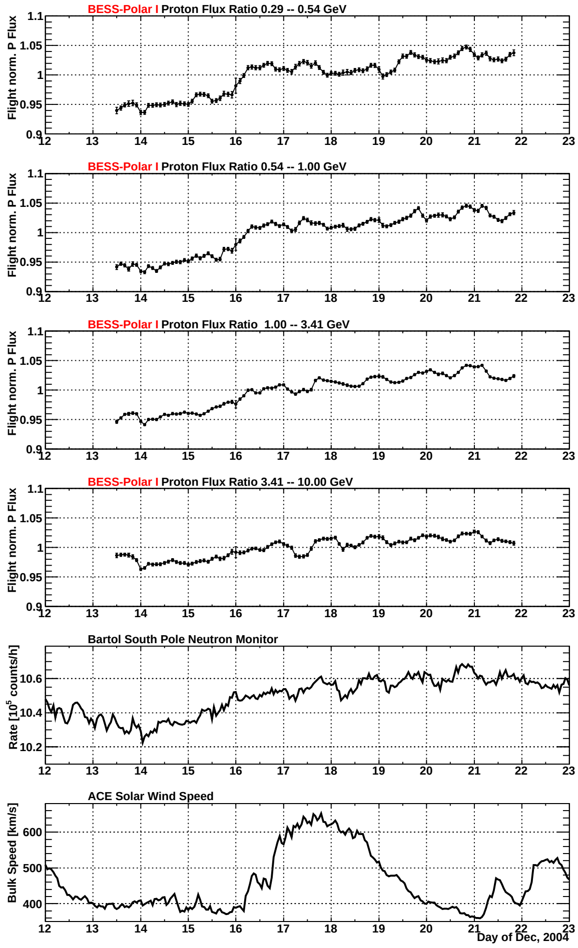

Fig. 3. Top panels show the proton flux for 4-hour time intervals normalized to the flight-averaged flux, for the energy ranges 0.29–0.54, 0.54–1.0, 1.0–3.4, and 3.4–10.0 GeV, respectively. For comparison, the Bartol neutron monitor and ACE solar wind speed are also shown for the same time window.

depth used for this atmospheric correction is derived from the live-time weighted residual pressure measured during the respective time interval corrected for the cosine effect of the mean incident angle.

We selected proton events from the data set and derive a proton flux at the TOA. To study changes in the proton flux, the flight data was divided into 4 hour time intervals yielding sufficient event numbers to determine a proton spectrum up the energy range of 10-34 GeV with a statistical uncertainty of less than 0.5%. Adjacent time intervals had an overlap of half the interval width, dividing the 8.5 day long science flight into 102 intervals. For each time interval, a proton flux at TOA was determined for the energy ranges: 0.29–0.54, 0.54–1.0, 1.0–3.4, and 3.4–10.0 GeV, respectively. All fluxes shown here are normalized to the flight averaged proton flux.

IV. Results

The technique described in section III has been used to derive a proton flux at the TOA for 4 hour intervals, which was then normalized to the flight average proton flux. The resulting relative flux versus time is shown in Fig. 3 together with the Bartol South Pole neutron monitor and the ACE/SWEPAM solar wind speed. Fig. 4 provides more details on the solar wind during the flight.

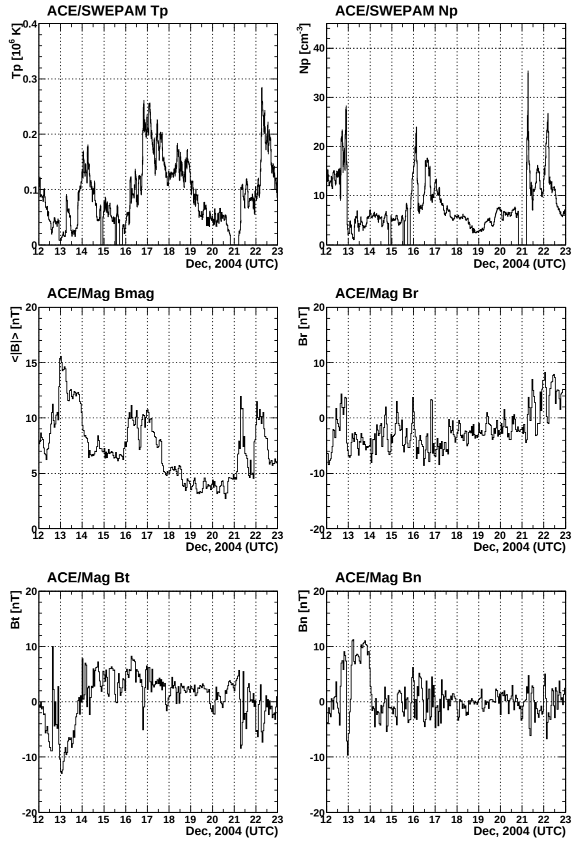

Fig. 4. ACE/SWEPAM Proton density, temperature, and ACE/MAG magnetic field component.

The BESS-Polar I proton data clearly exhibits flux variation over a broad energy range. Early in the BESS-Polar I flight, the late stage of the gradual flux decrease can be seen. On Dec 14, the proton flux starts to recover in all energy bins shown. This recovery rate is softened when a high speed stream reaches Earth. It is noteworthy that on Dec 15 the proton flux below 1.0 GeV recovers more rapidly than for higher energies. As expected, the higher energy GCR are less affected by solar activity. The flux for proton below and above 3.41 GeV changes by approximately 10% and 5%, respectively.

As the high-speed stream sweeps by Earth, the magnetic field seen by ACE is more orderly and may indicate a return to a steady-state configuration (Dec 17, 12:00). At the same time the diurnal variation becomes most apparent in the highest energy bin (3.14–10.0 GeV). We have extensively studied potential instrument related changes that could account for the periodic changes in the proton data. No instrumental or efficiency changes could be found that would have the appropriate phase and amplitude to the proton flux. The correlated onset of the diurnal variation in the upper energy bin and the more organized magnetic field may only be coincidental,

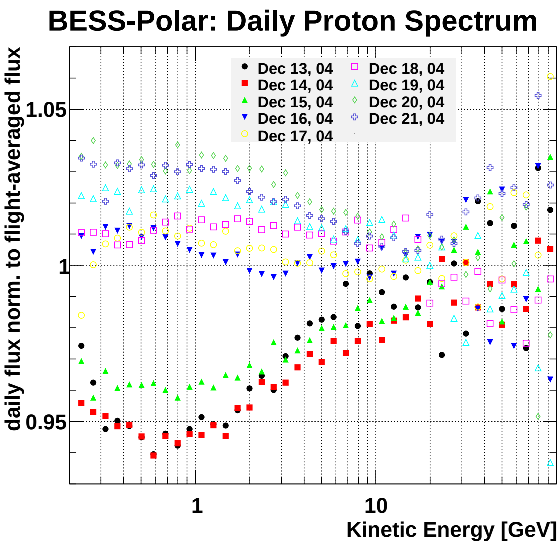

Fig. 5. Daily Proton normalized to the BESS-Polar flight-averaged proton flux.

since at the same time the payload is leaving the low geomagnetic cut-off region and is approaching geomagnetic cut-off values similar to those at the South Pole neutron monitor. With the present data set, we can not resolve this ambiguity. However, in the second BESS-Polar flight (2007) this low geomagnetic cut-off region was sampled twice. The search for flux variation in BESS-Polar II will allow us to study the correlation of diurnal variation and geomagnetic cut-off.

Fig. 5 shows the flight normalized proton spectra for each day and emphasizes the spectral changes during the flight. The spectrum of Dec 13 reflect the flux decline and the spectra of Dec 14 & 15 show the onset of the gradual recovery. From Dec 15 to Dec 16, the protons below ~1 GeV recover more rapidly than the proton between 1–4 GeV which is consistent with the recovery in Fig. 3. After Dec 19 the spectral shape is not changing and is only shifting little in magnitude, which is consistent with the slower recovery and an averaging out of the diurnal variation. In this fine energy bining the flux above 20 GeV is is limited by statistics, but based on an extrapolation from lower energies, the flux 20–30 GeV is not affected be the solar transient solar activity.

V. Discussion and Outlook

In this paper, we have demonstrated that the BESS-Polar instrument in its 2004 flight is a sensitive tool to study GCR flux variation caused by transient effects on the sun and in the heliosphere. The BESS-Polar data extent the energy of the other space-based direct measurements to several 10 GeV. The observed gradual flux changes see by BESS-Polar are in very good agreement with data from the South Pole neutron monitor and ACE spacecraft. However, the BESS-Polar data provide a direct measurement to much higher energies. The BESS-Polar I data exhibit diurnal flux variation as does the South Pole neutron monitor, but BESS-Polar data show a slight phase difference in the time of the maxima. This could be explained by the fact that the neutron monitor is stationary with respect to the geomagnetic field and the BESS-Polar payload is circumnavigating the geographical South Pole at $\sim 36^o$ per day

VI. Acknowledgements

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