Successive Measurements of Cosmic-Ray Antiproton Spectrum in a Positive Phase of the Solar Cycle

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Abstract

The energy spectrum of cosmic-ray antiprotons ($\bar{p}$'s) has been measured by BESS successively in 1993, 1995, 1997 and 1998. In total, 848 $\bar{p}$'s were clearly identified in energy range 0.18 to 4.20 GeV. From these successive measurements of the $\bar{p}$ spectrum at various solar activity, we discuss about the effect of the solar modulation and the origin of cosmic-ray $\bar{p}$'s. Measured $\bar{p}/p$ ratios were nearly identical during this period, and were consistent with a prediction taking the charge dependent solar modulation into account.

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Key words: Cosmic-ray, Antiproton, Measurements, Solar modulation
1 Introduction

The origin of cosmic-ray antiprotons ($\bar{p}$'s) is still holding a fundamental question even after their spectrum has been measured precisely in our previous work [1]. In recent solar-minimum period, we have collected 458 $\bar{p}$'s in the energy range between 0.18 and 3.56 GeV and observed a clear peak in the spectrum around 2 GeV, a generic feature of "secondary" $\bar{p}$'s which are produced by the interaction of Galactic high-energy cosmic-rays with the interstellar medium. It has become evident that the dominant component of cosmic-ray $\bar{p}$'s is the secondary $\bar{p}$'s. While the energy spectrum and absolute flux are well reproduced by several theoretical calculations [2,3], there remains some diversity among those calculations in the low energy region. They seem to arise from the different treatment of tertiary interactions of $\bar{p}$'s with the interstellar medium, $\bar{p}$ production mechanism such as nuclear sub-threshold effects, galactic propagation and solar modulations. Moreover, although the data have still large statistical errors at low energies, the observed flux appears to be higher than those calculations in the low energy region below 1 GeV where the secondary flux decreases sharply. Therefore, we can not rule out the primary origins, such as annihilation of neutralinos [2,4,5] or evaporation of primordial black holes [6,7].

The cosmic-ray particles are decelerated in entering the heliosphere by the expanding solar magnetic disturbances, and their energy spectra observed at 1 A.U. should be deformed. The flux variation is expected to be small for secondary $\bar{p}$'s at low energies because of their relatively hard spectrum, while any softer component would exhibits a large variation. It has been pointed out that additional soft component from a novel source can be singled out by measuring the $\bar{p}$ spectra at different solar periods [5]. It has been recently suggested that the solar magnetic polarity and the charge dependent effect cannot be neglected and the modulation follows a 22-year cycle rather than an 11-year cycle [3]. Actually, measurements of $e^-$/He$^{2+}$ ratio [8] and $e^-$/p$^+$ ratio [9] variations over a long period appear to support this charge dependence. Since protons and antiprotons are different only in their charge sign, the simultaneous measurements of both particles are most suitable for studying the charge dependence of solar modulation.

We report here a new measurement of cosmic-ray $\bar{p}$ spectrum in the energy range between 0.18 and 4.20 GeV, based on 384 events detected by the BESS spectrometer in 1998 flight. In total, 848 $\bar{p}$ events has been accumulated from the measurement in successful four flights in 1993, 1995, 1997 and 1998. The

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spectrum measured in 1998 is compared with the previous results [1,10–14], in order to observe changes with solar activity.

2 BESS Detector

The BESS detector, shown in Fig. 1, was proposed and developed as a high-resolution spectrometer to perform searches for rare cosmic-rays as well as precision measurements on absolute fluxes of various cosmic-ray particles [15–17]. Various new detector technologies developed for collider experiments were incorporated to the spectrometer. A uniform field of 1 Tesla was produced by a thin (4 g/cm$^2$) superconducting coil [18], through which particles could pass with small interaction probability. The magnetic-field region was filled with central tracking devices. This configuration achieved a geometrical acceptance of 0.3 m$^2$Sr, and it was an order of magnitude larger than those of previous cosmic-ray spectrometers for balloon experiments. The $r\phi$ tracking in the central region was performed by fitting up to 28 hit-points, each with 200 µm resolution, in a jet-type drift (JET) chamber and two inner drift chambers (IDC’s) resulting in a magnetic-rigidity ($R \equiv Pc/Ze$) resolution of 0.5 % at 1 GV/c. Tracking in the z coordinate was done by fitting points in IDC’s measured by vernier pads with an accuracy of 470 µm and points in the JET chamber measured by charge division with an accuracy of 2.5 cm. The continuous and redundant 3-dimensional tracking enabled us to recognize multi-track events and tracks having interactions or scatterings, thus minimizing such backgrounds. The upper and lower scintillator hodoscopes [19] measured two independent $dE/dx$ and the time-of-flight (TOF) of particles. In addition, $dE/dx$ in the drift chamber gas was obtained as a truncated mean of the integrated charges of the hit-pulses. The scintillator hodoscopes consisted of ten upper and twelve lower plastic scintillators and photo-multiplier tubes (PMT’s) attached at each end of scintillators. The hodoscopes were placed at outer-most radii and the timing resolution of each hodoscope was 55 psec rms, resulting in $\beta^{-1}$ resolution of 0.014, where $\beta$ is defined as particle velocity divided by the speed of light. Furthermore a Cherenkov counter [20] with silica-aerogel radiator [21] was installed below the upper TOF hodoscopes. We selected the radiator having a refractive index of 1.020 (while 1.032 for BESS 1997), in order to veto $e^-/\mu^-$ backgrounds up to 4.2 GeV.

In 1998 flight, the payload was launched on July 29 from Lynn Lake, Manitoba to Peace River, Alberta in northern Canada, where the cut-off rigidity is less then 0.5 GV/c. The scientific data were taken for a live time of 60462 sec at altitudes ranging from 37.4 to 35.7 km (with residual air of 4.8–5.3 g/cm$^2$). All the detector components worked well during the flight and 19 million cosmic-ray events were recorded onto two magnetic tapes (the total recorded data size was 33.5 Gbytes). The first-level trigger was provided by a coincidence
between the top and the bottom scintillators, with the threshold set at 1/3 of the pulse height from minimum ionizing particles. The second-level trigger, which utilized the hit-patterns of the scintillator-hodoscopes and the inner drift chambers (IDC), first rejected unambiguous null- and multi-track events and then made a rough rigidity-determination to select negatively-charged particles predominantly. In addition, one of every 60 first-level triggered events were recorded in order to build a sample of unbiased triggers.

3 Analysis

Since the BESS instrument had highly symmetrical detector-configuration, we assumed that $\bar{p}$’s behaved similarly as protons in the instrument except for deflection in the magnetic field and the inelastic interactions. Thus, all selection criteria were defined based on the measured properties of protons. At first, we selected events with (i) a single down-going particle fully contained in the fiducial region of the tracking volume, (ii) only one hit in the upper TOF hodoscope and (iii) one or two hits in the lower TOF hodoscope. Then the following cuts were applied in order to ensure correct measurements. (1) The numbers of used hits in the $r\phi$-fitting and in the $z$-fitting should be more than 10 and 6, respectively: (2) The reduced $\chi^2$ of the fitted $r\phi$ and $z$ track had to be less than 6.5 and 6.0, respectively: (3) Since signals from some PMT’s were somewhat noisy, we rejected wrong hits in the TOF hodoscopes for better TOF measurement: (4) The $z$ position determined from the left-right time difference measured by the PMT’s should match the $z$-impact point of the extrapolated track at the TOF hodoscopes: (5) The ratio of the signal amplitude of the left and right PMTs should be consistent with the $z$-impact point of the extrapolated track: The instrument was suspended with the balloon via a parachute (50m H × 1m φ) of 340 kg, situated 24 meter above the instrument. Particles passing through the parachute would interact and change their energy. Therefore, (6) the extrapolated track should not pass through the parachute: (7) The three $dE/dx$ measurements in the scintillator-hodoscopes and JET chamber were loosely required as functions of $R$ to be compatible with proton or $\bar{p}$: (8) The proper value of $1/\beta$ was required as a function of $R$: The combined efficiency of these off-line selections was 71 – 75 % for $R$ from 0.5 to 5 GV/c.

These simple and highly-efficient selections were sufficient for a very clean detection of $\bar{p}$’s in the low velocity ($\beta < 1/1.15$) region. At higher velocities, the $e^-/\mu^-$ background started to contaminate the $\bar{p}$ band, where we required the Cherenkov veto; i.e., (1) the particle trajectory to traverse the fiducial volume of the aerogel, and (2) the Cherenkov output to be less than 0.09 of the mean output from $e^-$. This cut reduced the acceptance by 20 %, but rejected $e^-/\mu^-$ backgrounds by a factor of 4400, while keeping 92 % efficiency.
for protons and $\bar{p}$'s which crossed the aerogel with rigidity below the threshold (4.7 GV/c).

Fig.2 shows the $\beta^{-1}$ versus $R$ plot for the surviving events. We see a clean narrow band of 384 $\bar{p}$'s at the exact mirror position of the protons. The $\bar{p}$ band was slightly contaminated with the $e^-/\mu^-$ backgrounds due to the inefficiency of the aerogel Cherenkov counter, and in the flux calculation we subtracted this background whose amount was estimated as follows: (1) We counted the number of $e^-/\mu^-$ events overlapping with the $\bar{p}$ band before the requirement on the Cherenkov output. (2) We obtained the probability that $e^-/\mu^-$ gave a lower Cherenkov output than the threshold, from the distribution of the output for high rigidity protons ($\geq 25$ GV) which should emit enough output. (3) From the above two quantities we estimated the amount of the $e^-/\mu^-$ background as 0 %, 0.6 % and 4.2 % at 0.25, 2 and 4 GeV, respectively. Backgrounds of albedo and of mis-measured positive-rigidity particles were totally excluded by the excellent $\beta^{-1}$ and $R^{-1}$ resolutions. To check against the “re-entrant albedo” background, we confirmed that the trajectories of all $\bar{p}$'s can be traced numerically through the Earth’s geomagnetic field back to the outside of the geomagnetic sphere.

We obtained the $\bar{p}$ energy spectrum at the top of the atmosphere (TOA) in the following way: The geometrical acceptance of the spectrometer was calculated by a Monte Carlo simulation [22], which was consistent with an analytical calculation [23]. The fraction of the live data-taking time was directly measured as 86.4 % by counting 1 MHz clock. The efficiencies of trigger and of the off-line selections were determined by using protons in the unbiased trigger samples. The TOA energy of each event was calculated by tracing back the particle through the detector material and the air. The survival probability of the $\bar{p}$'s through the air and instrument was evaluated by GEANT/GHEISHA simulation [22], which incorporated detailed material distribution, realistic detector performance and correct $\bar{p}$-nuclei cross sections [24]. The $e^-/\mu^-$ background was subtracted, whose amount is described above. And we subtracted the expected number of atmospheric $\bar{p}$'s, produced by the collisions of cosmic rays in the air. The subtraction amounted to $17 \pm 3$, $21 \pm 4$ and $22 \pm 6$ % at 0.3, 0.7 and 2 GeV, respectively, where the errors correspond to the maximum difference among the three independent recent calculations [25–27]. Table 1 contains resultant 1998 $\bar{p}$ fluxes and $\bar{p}/p$ flux ratios at TOA. The first and the second error represent the statistical [28] and systematic errors, respectively. The dominant systematic error at low energies is the uncertainty in the evaluation of the interaction losses, to which we attribute $\pm 15$ % relative error. At high energies, the uncertainty in the atmospheric $\bar{p}$ calculation becomes dominant. The statistical errors are always larger than the systematic errors by a large factor especially at the low energies.
Fig. 3 shows the BESS 1998 $\bar{p}$ spectrum, together with the previous measurements [1,10–14]. By using 1998 flight data, we have measured the $\bar{p}$ spectrum in a wider energy region of 0.18 to 4.20 GeV and detected again a clear peak around 2 GeV as we did in 1997. As recently pointed out [5], increase of solar activity suppresses any soft primary $\bar{p}$ component while only modestly affects the secondary $\bar{p}$ spectrum. The solar activity at the time of the BESS 1998 flight was greater than the 1995 and 1997 flights [29]. Therefore, the shape of the 1998 spectrum should be closer to the shape of the spectrum composed only of secondary $\bar{p}$, even if the primary $\bar{p}$'s existed. Shown also in Fig.3 is a recent theoretical calculation [30] for the secondary $\bar{p}$ at the BESS 1998 flight (solar modulation parameter $\phi_{98}=610$MV, which was determined from BESS 1998 proton spectrum [33]). In the whole energy region, this calculation agrees well with our spectrum at 86% confidence level. This implies that secondary $\bar{p}$ is the dominant component of the cosmic-ray $\bar{p}$'s and the model used for the calculation is basically correct. The expected spectrum at BESS 1997 was also calculated in the same way by using the solar modulation parameter $\phi_{97}=500$MV as represented by the dashed curve in Fig.3. It appears to be insensitive to the change of the modulation parameter. This is because the interstellar $\bar{p}$ flux steeply drops toward the low energy in contrast to the interstellar proton spectrum [34]. In fact, the measured spectra are nearly constant in the peak region. However, in the low energy region (0.18 – 0.78 GeV), the agreement between the 1997 spectrum and the calculation is less consistent. Moreover, the 1995 spectrum shows larger deviation from the calculation in spite of similar modulation parameter ($\phi_{95}=540$MV) as the BESS 1997. This might be due to statistical fluctuation, or might suggest a contribution of low-energy primary $\bar{p}$ from novel source such as annihilation of neutralinos [2,4,5] or the evaporating primordial black holes [6,7]. Because $\bar{p}$'s from these “primary” sources, if they exist, are expected to be prominent at low energies and to exhibit large solar modulations [5].

In order to study the solar modulation, the $\bar{p}/p$ ratio is more adequate, which is expected to clarify the charge-dependence of the solar modulation [3]. In Fig. 4 the BESS 1998 $\bar{p}/p$ ratio shows almost similar spectrum as the spectrum at the solar minimum (the 1997 data), especially around 2 GeV where we have better statistics. The lowest energy point of our data might suffer some uncertainties in the proton flux due to large subtraction of atmospheric secondary protons, which is significant in the low energy region [33]. Despite the general advantage of taking $\bar{p}/p$ ratio to cancel various systematic errors, such as live-time and geometrical acceptance, it should be noted that the most significant systematic errors in the analysis come from the uncertainties in the atmospheric $\bar{p}$ calculation and in the interaction losses, which can not be canceled even in the form of the ratio. Taking the charge-dependence of the solar
modulation into account [3], (i) the $\bar{p}/p$ ratio is expected to be nearly identical during the positive Sun's polarity phase; and (ii) when the polarity switches into the negative, the $\bar{p}/p$ ratio shall rapidly increase as represented by the dotted curve in Fig. 4. The BESS 1993, 1995, 1997 and 1998 spectra, measured in the positive polarity phase, were nearly identical as shown in Fig. 4 and consistent with the prediction. It can be more clearly understood in the form of the ratios of $\bar{p}/p$ ratio as shown in Fig. 5. The ratios of $\bar{p}/p$ ratio normalized by the BESS 1997 data are consistently distributed around the unity within the statistical fluctuation.

Our measurements on the $\bar{p}/p$ ratio are consistent with the prediction taking the charge dependent solar modulation into account. However, it is too early to conclude that the evidence for the charge dependence is exhibited. We are planning further annual flights in the following solar-maximum period in which the polarity switches into the negative. The observation of the increase would be a definite evidence for the importance of the charge dependent effect in the solar modulation. At the same time, measurements of the $\bar{p}$ spectrum through the solar-maximum period itself have a crucial importance to determine the origin of the low energy $\bar{p}$'s. As previously mentioned, any soft $\bar{p}$ component from the primary sources would be suppressed as the solar activity increases, while the secondary $\bar{p}$ spectrum is affected modestly. Therefore, to observe variations in the low energy region would help us to draw a firm conclusion on whether we are seeing the primary $\bar{p}$'s from novel sources.

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References

[1] S. Orito, et al., Phys. Rev. Lett. 84 (2000) 1078.
[2] L. Bergström, et al., Proc. 26th Int. Cosmic Ray Conf. (Utah) 2 (1999) 285.
[3] J. W. Bieber, et al., Phys. Rev. Lett. 83 (1999) 674.
[4] S. Silk and M. Srednicki, Phys. Rev. Lett. 53 (1984) 624.
[5] T. Mitsui, K. Maki and S. Orito, Phys. Lett. B 389 (1996) 169.
[6] S. W. Hawking, Commun. Math. Phys. 43 (1975) 199.
[7] K. Maki, T. Mitsui and S. Orito, Phys. Rev. Lett. 76 (1996) 3474.
[8] M. Garcia-Munoz, et al., Proc. 22nd Int. Cosmic Ray Conf. (Dublin) 3 (1991) 497.
[9] A. Raviart, et al., Proc. 25th Int. Cosmic Ray Conf. (Durban) 2 (1997) 37.
[10] K. Yoshimura, et al., Phys. Rev. Lett. 75 (1995) 3792; A. Moiseev, et al., Astrophys. J. 474 (1997) 479.
[11] J. W. Mitchell, et al., Phys. Rev. Lett. 76 (1996) 3057.
[12] M. Boezio, et al., Astrophys. J. 487 (1997) 415, and references therein.
[13] H. Matsunaga, et al., Phys. Rev. Lett. 81 (1998) 4052.
[14] G. Basini, et al., Proc. 26th Int. Cosmic Ray Conf. (Utah) 3 (1999) 77.
[15] S. Orito, KEK Report 87-19, p.111, 1987, Proceedings of the ASTROMAG Workshop, edited by J. Nishimura, K. Nakamura, and A. Yamamoto.
[16] A. Yamamoto, et al., Adv. Space Res. 14 (1994) (2)75.
[17] Y. Ajima, et al., Nucl. Instrum. Methods A 443 (2000) 71.
[18] A. Yamamoto, et al., IEEE Trans. Magn. 24 (1988) 1421.
[19] Y. Shikaze, et al., Nucl. Instrum. Methods A (in printing).
[20] Y. Asaoka, et al., Nucl. Instrum. Methods A 416 (1998) 236.
[21] T. Sumiyoshi, I. Adachi, R. Enomoto, T. Iijima, R. Suda, M. Yokoyama, Silica aerogels in high energy physics Journal of Non-Crystalline Solids 225 (1998) 369–374.
[22] H. Matsunaga, Ph.D. thesis, University of Tokyo, 1997.
[23] J. D. Sullivan, Nucl. Instrum. Methods 95 (1971) 5.
[24] K. Nakamura, et al., Phys. Rev. Lett. 52 (1984) 731; V. F. Kuzichev, et al., Nucl. Phys. B 576 (1994) 581; Yu. P. Gorin, et al., Yad. Fiz. 18 (1973) 336; J. C. Allaby, et al., Yad. Fiz. 12 (1970) 538; V. N. Afonas’ev, et al., Yad. Fiz. 40 (1984) 34; V. N. Afonas’ev, et al., Yad. Fiz. 47 (1988) 1656; A. S. Carroll, et al., Phys. Lett. B 80 (1979) 319.
[25] T. Mitsui, Ph.D. thesis, University of Tokyo, 1996; T. Mitsui, S. Orito, and J. Nishimura, (in preparation).
[26] Ch. Pfeifer, U. Heinbach and M. Simon, Phys. Rev. C 54 (1996) 882.
[27] S. A. Stephens, Astropart. Phys. 6 (1996) 229.
[28] G. J. Feldman and R. D. Cousins, Phys. Rev. D 57 (1998) 3873.
T. Mitsui, et al. (to be published): The $\bar{p}$ spectra were calculated in the leaky box model. For the tertiary interaction of $\bar{p}$, a model which fit data was used instead of flat energy distribution of the emerging $\bar{p}$. A $\beta$ dependent escape-length was used, which obtained in Ref.[31]. The spectra were solar-modulated by following Ref.[32].

[31] S. A. Stephens, et al., Astrophys. J. 505 (1998) 266.

[32] L. A. Fisk, J. Geophys. Res. 76 (1971) 221.

[33] T. Sanuki, et al., Astrophys. J. (in printing).

[34] A. W. Labrador, et al., Astrophys. J. 480 (1997) 371.
Table 1
Antiproton fluxes (in $\times 10^{-2}$ m$^{-2}$s$^{-1}$sr$^{-1}$GeV$^{-1}$) and $\bar{p}/p$ ratios (in $\times 10^{-5}$) at TOA. $T$ (in GeV) define the kinetic energy bins. $N_p$ and $T_{\bar{p}}$, respectively, are the number of observed antiprotons and their mean kinetic energy in each bin.

| $T$ (GeV) | $N_p$ | $T_{\bar{p}}$ | $\bar{p}$ flux | $\bar{p}/p$ ratio |
|-----------|-------|---------------|----------------|------------------|
| 0.18 - 0.28 | 2     | 0.24          | 0.34$^{+0.48}_{-0.23}$ +0.06 | 0.20$^{+0.29}_{-0.14}$ +0.04 |
| 0.28 - 0.40 | 6     | 0.36          | 0.74$^{+0.48}_{-0.32}$ +0.09 | 0.42$^{+0.27}_{-0.18}$ +0.06 |
| 0.40 - 0.56 | 15    | 0.52          | 1.30$^{+0.44}_{-0.37}$ +0.14 | 0.86$^{+0.29}_{-0.25}$ +0.13 |
| 0.56 - 0.78 | 22    | 0.68          | 1.23$^{+0.38}_{-0.33}$ +0.13 | 0.95$^{+0.29}_{-0.26}$ +0.14 |
| 0.78 - 0.92 | 23    | 0.84          | 2.19$^{+0.60}_{-0.53}$ +0.21 | 1.97$^{+0.54}_{-0.48}$ +0.27 |
| 0.92 - 1.08 | 25    | 1.00          | 2.30$^{+0.65}_{-0.52}$ +0.21 | 2.38$^{+0.67}_{-0.54}$ +0.32 |
| 1.08 - 1.28 | 21    | 1.20          | 1.76$^{+0.58}_{-0.52}$ +0.16 | 2.25$^{+0.74}_{-0.66}$ +0.31 |
| 1.28 - 1.52 | 41    | 1.42          | 3.30$^{+0.65}_{-0.58}$ +0.29 | 4.93$^{+0.97}_{-0.87}$ +0.65 |
| 1.52 - 1.80 | 29    | 1.66          | 1.81$^{+0.49}_{-0.43}$ +0.20 | 3.09$^{+0.84}_{-0.73}$ +0.46 |
| 1.80 - 2.12 | 37    | 1.94          | 2.23$^{+0.54}_{-0.46}$ +0.23 | 5.22$^{+1.26}_{-1.08}$ +0.74 |
| 2.12 - 2.52 | 42    | 2.28          | 2.07$^{+0.50}_{-0.36}$ +0.18 | 5.74$^{+1.38}_{-1.00}$ +0.77 |
| 2.52 - 3.00 | 46    | 2.80          | 2.00$^{+0.45}_{-0.33}$ +0.22 | 7.20$^{+1.63}_{-1.19}$ +1.06 |
| 3.00 - 3.56 | 46    | 3.30          | 1.89$^{+0.45}_{-0.29}$ +0.25 | 9.24$^{+2.21}_{-1.44}$ +1.54 |
| 3.56 - 4.20 | 29    | 3.83          | 1.84$^{+0.58}_{-0.32}$ +0.26 | 11.63$^{+3.66}_{-2.05}$ +2.01 |
Fig. 1. Cross-sectional view of the BESS 1998 detector with one of the $\bar{p}$ events.
Fig. 2. The identification of $\bar{p}$ events. The solid curves define the $\beta^{-1} - R$ region and the $\bar{p}$ mass band used for the spectrum measurement.
Fig. 3. The BESS 1998 antiproton spectrum at the top of the atmosphere, together with the previous data. The thick solid curve represents the expected spectrum for secondary $\bar{p}$ [30] at the 1998 flight ($\phi_{98}=610\text{MV}$) and well reproduces the BESS 1998 spectrum in the whole energy region. The expected spectrum at the 1997 flight ($\phi_{97}=500\text{MV}$) was also calculated in the same way as the 1998, represented by the thick dashed curve. Although the curve agrees with the BESS 1997 spectrum in the peak region, the agreement is less consistent in the low energy region. Also shown are other calculations [2,3] for secondary $\bar{p}$ at solar minimum (corresponding to the solar activity level at the BESS 1997 flight).
Fig. 4. Comparison of the BESS 1993, 1995, 1997 and 1998 $\bar{p}/p$ ratios with previous data [12], and the calculation [3] taking the charge dependence of the solar modulation into account. The solid and dashed curves represent the expected $\bar{p}/p$ ratio at the solar minimum and at the solar maximum in the positive Sun’s polarity. When the polarity switches, the ratio is expected to increase as represented by the dotted curve.
Fig. 5. The ratios of the $\bar{p}/p$ ratio normalized by the BESS 1997 data are distributed around the unity within the statistical fluctuation. The BESS 1993, 1995, 1997 and 1998 data were measured in the positive polarity phase. Therefore, it is shown that the $\bar{p}/p$ ratio is nearly identical during the positive polarity phase.