ANTIPARTICLES

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Abstract. Nearly a half century after the discovery of the antiproton the study of cosmic-ray antimatter continues to be an exciting and fertile field. Sensitive searches for heavy cosmic-ray antimatter continue, although in recent years their value as a probe of universal baryon symmetry has all but evaporated. Antiprotons and positrons have opened new windows on the origin and history of cosmic rays. The rarity of antimatter as compared to ordinary cosmic-ray species has posed substantial experimental challenges. Early reports of significant enhancements of antiprotons and high-energy positrons fueled speculation that non-baryonic dark matter had been found. A new generation of balloon-borne magnetic spectrometers employing powerful particle identification techniques to eliminate background have finally managed to uncover the true antimatter signal. These new measurements support simple models of secondary production but also suggest the possibility of a small yet interesting primary component.

1. Introduction

Ever since antiprotons were discovered at the Lawrence Berkeley Bevalac in the mid 1950's, scientists have speculated that the symmetry between matter and antimatter, so evident on a microscopic scale, might apply to the universe as a whole. Whereas cosmic rays could contain a small extragalactic component it was thought that the baryon symmetry of the universe could be studied by searching for cosmic-ray antimatter. The detection of a single antihelium nucleus would be sufficient to reveal cosmic antimatter domains and the detection of a single heavy nucleus would require the existence of an antistar. Nevertheless nearly five decades of cosmic-ray antimatter searches have turned up empty handed. Now it appears that intergalactic magnetic fields present an impenetrable barrier to diffusion of cosmic rays over cosmological distances and limits on the diffuse gamma radiation constrain antimatter domains to scales larger than that of the horizon.

In recent years considerable attention has turned to Galactic antimatter. Positrons and antiprotons are naturally produced as secondaries in collisions of high-energy cosmic rays with the interstellar medium (ISM). Being the only secondaries of protons, the dominant cosmic-ray component, the energy spectra of these antiparticles contain valuable information about the conditions under which protons propagate through the Galaxy. The rarity of these species has presented great technical challenges for their detection and early measurements were plagued by background. It has only been in the last five years that balloon-borne instruments with powerful

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particle identification have been able to cut through these backgrounds and reliably measure the true antimatter spectra.

With the improvement of these spectral measurements we may be seeing the first hint of spectral components not anticipated by pure secondary production models. A particularly exciting possibility is that features being observed may be due to the annihilation of supersymmetric dark matter in the Galactic halo.

2. Extragalactic Antimatter

Steady advances in detector technology have resulted in significant improvements in the limits on the fraction of heavy antimatter in the cosmic radiation (see Figure 1). The introduction of lightweight superconducting magnets and the use of precision continuous tracking to reject the hard scatter background of ordinary nuclei have resulted in the best limits to date. With multiple balloon flights at low cut-off rigidity the BESS experiment (Orito *et al.*, 2000) has set limits of 10^{-6} on the ratio $\overline{\mathrm{He}}/\mathrm{He}$ and could reach 10^{-7} with continuing flights. In comparison, the relatively unsophisticated AMS space instrument (Alcaraz *et al.*, 1999) with a smaller magnetic field and greatly reduced number of tracking layers, failed to surpass the BESS experiment despite a larger aperture and longer exposure without an atmospheric overburden.

In light of the substantial resources now being devoted to this effort it is appropriate to ask whether the continued reduction of these limits is worthwhile. In the past it has been argued that extragalactic antimatter could begin to reveal itself at the level of 10^{-7}–10^{-6} of ordinary cosmic rays (Ahlen *et al.*, 1982). These estimates however, did not take into account constraints on intergalactic transport.

Galactic magnetic fields are typically $\sim$ several μG. Simple flux freezing arguments suggest that an intergalactic (IG) field associated with these fields is ~ 1 nG. The leakage of large dipolar galactic fields into IG space implies a minimum of 10^{-12} G. Such fields would provide an impenetrable barrier against diffusion of ordinary ($\sim$ GeV) cosmic rays through intergalactic space. The only exception to this is if they were be channeled between galaxies along magnetic field lines. Under such optimized conditions Adams *et al.* (1997) have argued that the volume of the universe, accessible to us through cosmic rays, has a radius of only 60 Mpc. Additionally, a small galactic accessibility required to ensure that cosmic rays will not be destroyed by galaxies en route prohibits cosmic rays from entering our own Galaxy.

Adams *et al.* (1997) and later Cohen *et al.* (1998) have shown that the observed diffuse gamma ray background is inconsistent with antimatter domains anywhere within the observable universe. These arguments taken together explain why no heavy antimatter nuclei have been detected. Although the baryon/antibaryon content of the universe remains an interesting question, cosmic rays are ineffective as a probe of a universal baryon asymmetry.

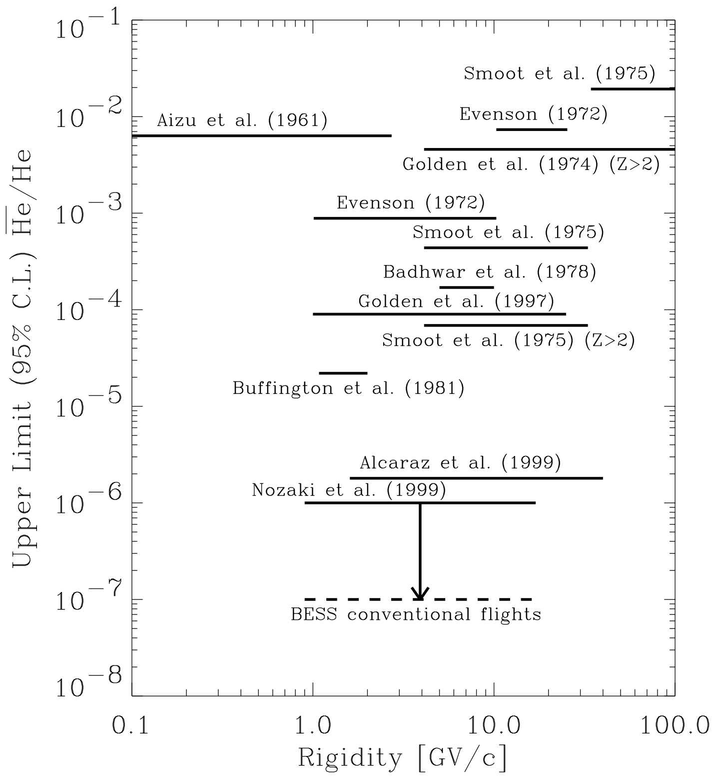

Figure 1. Upper limits for the $\overline{\mathrm{He}}$/He abundance ratio. In addition to the experimental limits, the expected result for the integrated BESS flights are shown (Nozaki *et al.*, 1999; Alcaraz *et al.*, 1999; Golden *et al.*, 1997, and references therein).

3. Antiprotons

Antiprotons are a natural consequence of the interaction of high energy cosmic rays with the ISM. For proton-proton collisions, kinematics suppresses production of protons with energies less than 1 GeV. Interactions of protons with heavier nuclei in the ISM have lower kinematic cut-offs. Additionally, the sharp low energy cut-off will be softened by solar modulation inside the heliosphere. Because antiprotons are secondaries, the $\bar{p}/p$ ratio is expected to decline above a few GeV (see Figure 2).

Early measurements of antiprotons were severely compromised by background induced through hard nuclear scattering and by inadequate particle identification. When Buffington *et al.* (1981) observed a flux of antiprotons at low energies, several orders of magnitude above expectations at that time, theorists speculated that he may have uncovered the annihilation of weakly interactive massive particles (WIMPs) present in the galactic halo at a level that would close the Universe (Silk and Srednicki, 1984; Stecker *et al.*, 1985; Hagelin and Kane, 1986). The

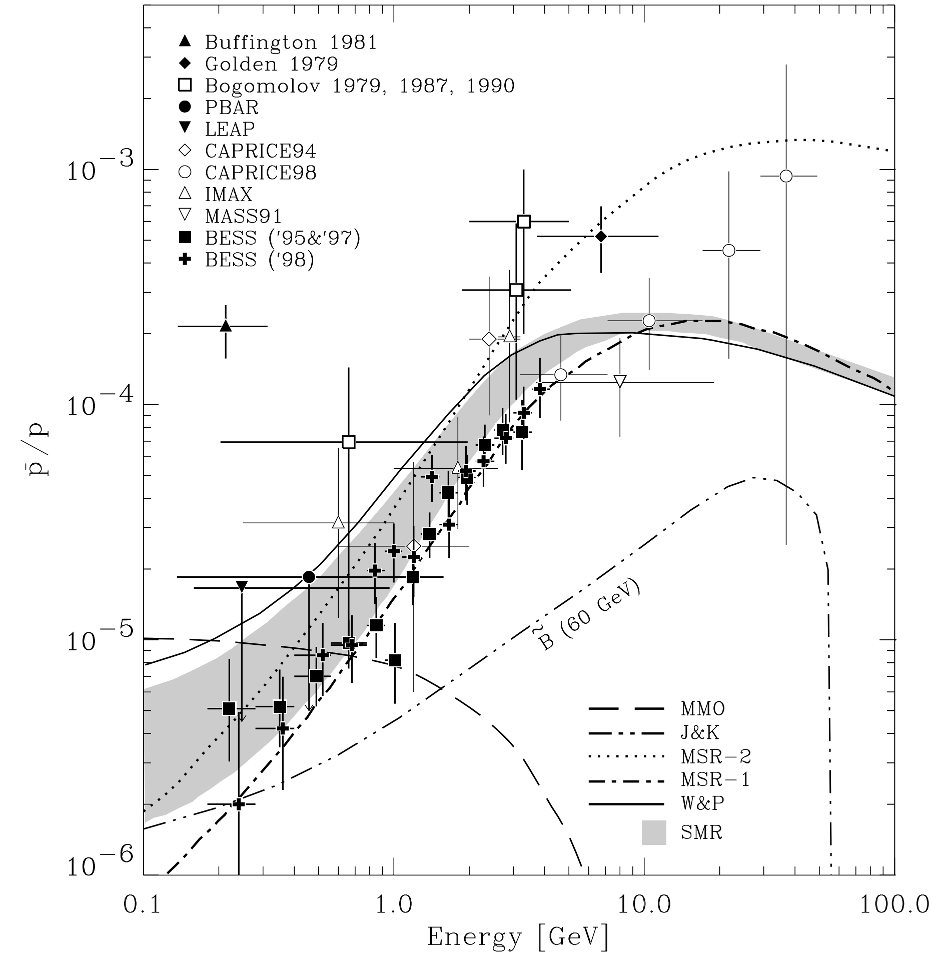

Figure 2. Compilation of observed $\bar{p}/p$ flux ratios at top of atmosphere, compared with model calculations for secondary and primary $\bar{p}$ production. Data from Buffington *et al.* (1981), Golden *et al.* (1979), Bogomolov *et al.* (1979, 1987, 1990), Salamon *et al.* (1990, PBAR), Streitmatter *et al.* (1990, LEAP), Boezio *et al.* (1997, CAPRICE94), Bergström *et al.* (2000, CAPRICE98), Mitchell *et al.* (1996, IMAX), Hof *et al.* (1996, MASS91), Orito *et al.* (2000 BESS, 95&97), Maeno *et al.* (2000, BESS). The theoretical calculations of the $\bar{p}/p$ ratio are from Moskalenko *et al.* (1998, MSR-1, MSR-2), Webber and Potgieter (1989, W&P), and Simon *et al.* (1998, SMR). Possible primary contributions to the $\bar{p}/$ spectrum arising from evaporating primordial black holes (Maki *et al.*, 1996), MMO) and from neutralino annihilation (Jungman and Kamionkowski, 1996, J&K) are also shown.

PBAR experiment (Salamon *et al.*, 1990) was the first to employ modern methods of particle identification (time-of-flight vs. Rigidity) to separate antiprotons from K^{-}s and μ^{-}s and continuous tracking to reject scattered protons. As a result, no low energy antiprotons were observed at levels substantially below that seen by Buffington *et al.* (1981). Subsequent experiments utilized this same technique to push the sensitivity even lower and have finally measured the antiproton flux at low energies (Orito *et al.*, 2000). Through repeated balloon flights the BESS collaboration has been able to precisely define the antiproton spectrum below several GeV. The results are in good agreement with secondary production models within the large uncertainties due to the poorly understood nature of solar modulation and interstellar proton reference spectra (see Figure 2).

The detailed measurements by BESS have rekindled interest in searching for a distortion of the secondary antiproton spectrum by a primary component consisting of antiprotons of exotic origin. Such a contribution to the $\bar{p}$ flux could arise from WIMP annihilation in the Galactic halo and indirectly reveal the presence of dark matter in the universe (Ellis *et al.*, 1988; Jungman and Kamionkowski, 1996). The low energy range below 100 MeV is particularly sensitive to the distinction between such a $\bar{p}$ component and the secondary antiproton flux. While the $\bar{p}$ spectrum falls sharply due to kinematic reasons, the calculated spectra for primary $\bar{p}$ from annihilating dark matter are nearly flat. Antiprotons from evaporating primordial black holes have also been suggested as a significant contribution to the $\bar{p}$ flux at energies below a few hundred MeV (Maki *et al.*, 1996). With some parameters, calculated primary antiproton spectra dominate the $\bar{p}$ flux from secondary production at low energies (see Figure 2) and precise measurements could reveal an 'exotic' component of the antiproton flux. Measurements in this energy region, however, are severely affected by solar modulation inside the heliosphere. In the coming years it may be possible to send instruments outside the heliosphere where such observations could be conducted (Wells *et al.*, 1999).

Extending antiproton measurements to higher energies required new techniques of particle identification. The IMAX experiment (Mitchell *et al.*, 1996) used aerogel Cherenkov detectors to perform antiproton measurements up to several GeV whereas the CAPRICE instrument (Boezio *et al.*, 1997) employed ring imaging techniques to measure antiprotons up to 50 GeV. The MASS91 experiment (Hof *et al.*, 1996), an improved version of the earlier Golden *et al.* (1979) experiment but with reduced background, has measured a lower $\bar{p}$ flux.

Although the three experiments suffer from low statistics at high energies, these instruments do not observe the predicted roll-over at these energies. Yet a continued rise in the $\bar{p}/p$ ratio would be difficult to explain theoretically. Extragalactic models which predict a $\bar{p}/p$ ratio which rises as $E^{0.6}$ are unlikely because of the arguments given in the previous section. Closed Galaxy models, while boosting the $\bar{p}/p$ ratio at high energy would lead to an overproduction of ^{3}He which has not been observed (Beatty *et al.*, 1993; Mitchell *et al.*, 1996). A rising $\bar{p}/p$ ratio above a few GeV does also develop in the self-consistent CR propagation model of Moskalenko *et al.* (1998) in the case of a nucleon injection spectrum much harder than locally observed (MSR-2 in Figure 2). Unlike models based on the local electron and proton spectra, a hard nucleon spectrum reproduces the observed high continuum gamma-ray emission above ~ 1 GeV well. As the authors point out, it is interesting that the locally observed $\bar{p}/p$ spectrum does not depend strongly on the details of the propagation. Its sensitivity to the nucleon injection spectrum above a few GeV however, makes this ratio an important test for CR models. In the energy range between several hundred MeV and 5 GeV, where statistically accurate data is available, a nucleon injection spectrum consistent with the local one describes the data well (MSR-1 in Figure 2).

4. Positrons

Like antiprotons, positrons are produced as secondaries of the interaction of cosmic-ray protons with the ISM. Due to their small mass, electrons and positrons lose energy more rapidly than protons and antiprotons and thus have a much steeper spectrum above several GeV. At all energies the ratio of protons to electrons is high (always > 100) although the reason for this remains a mystery.

Although secondary electrons and positrons are produced in pairs, the measured positron fraction $e^+/(e^+ + e^-)$ is of order $\approx 10\%$, indicating a substantial primary electron component. The positron fraction is expected to decline slowly with energy because of the declining path lengths at high rigidities of the primary protons. At energies below a few GeV, solar modulation has a significant impact on the spectral shape and can produce charge sign dependent effects that can alter the positron fraction during the solar cycle.

Before 1995, measurements of positrons were subject to the misidentification of the much more numerous protons and other hadrons. This background introduced a spurious rise in the positron fraction at high energies. In the last five years powerful new balloon instruments with improved hadron identification have been able to efficiently reject this background and have measured the true positron spectrum over a wide range of energies. The first experiment to do this was the HEAT-e$^\pm$ instrument which combined a transition radiation detector, an electromagnetic calorimeter, and a magnetic spectrometer. This combination provided a multiple redundant means to efficiently and reliably identify and reject hadronic background.

A compilation of recent measurements is shown in Figure 3 along with predicted flux ratios. The calculations by Protheroe (1982) are based on the measured electron and proton spectra within a Leaky Box model of cosmic-ray propagation while the more recent work by Moskalenko and Strong (1998) is the result of a self-consistent diffusion model of Galactic CR propagation. This model (Moskalenko & Strong ‘b’ in Figure 3) is based on a moderately hard ($\gamma = 2$) interstellar proton spectrum and produces the observed positron fraction well over a wide energy range. While a hard interstellar nucleon spectrum can explain the high observed diffuse gamma-ray flux at GeV energies (see the chapter on diffuse γ-rays by Strong and Moskalenko in this book), it is not supported by measurements of the local proton spectral index (see Section 3 and Strong *et al.*, 2000). A more likely scenario is the model ‘a’ in Figure 3 which is based on primary spectra consistent with local observations. Also shown in Figure 3 are predictions of the effect of

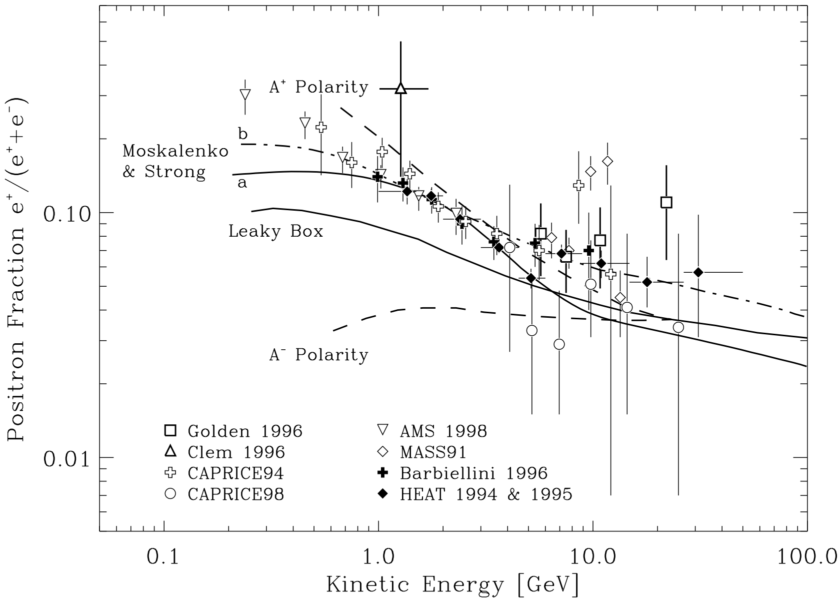

Figure 3. Positron fraction as a function of energy. Only recent measurements are shown (Golden *et al.*, 1996; Clem *et al.*, 1996; Boezio *et al.* 2000; Boezio *et al.*, 1999; Alcaraz *et al.*, 2000; Basini *et al.*, 1995; Barbiellini *et al.*, 1996; Barwick *et al.*, 1997). The theoretical curves are from Protheroe (1982) and Moskalenko and Strong (1998).

solar modulation for opposite solar epics during a 22 year cycle (Clem *et al.*, 1996) which illustrate the strong effect at low energies.

The data follows the general trend of the theoretical predictions, i.e the positron fraction decreases smoothly with energy above ≈ 1 GeV with one important exception: the presently best available data above 1 GeV (Barwick *et al.*, 1997) can not be easily explained in terms of conventional secondary production mechanisms. In particular, a feature is observed at energies above 7 GeV (see Figure 4) which is suggestive of a primary source of high-energy positrons (Coutu *et al.*, 1999). The authors discuss possible sources of such a primary e^+ component and model the expected contribution to the positron fraction. In their best fit to the data (solid line, Figure 4) the positrons originate as secondaries in the annihilation chain of 380 GeV neutralinos.

5. Discussion/Conclusions

Experimental progress in the search for antimatter during the past years has resulted in significantly improved limits. By continuing their successful balloon program, BESS can reach an upper limit of 10^{-7} for the $\overline{\text{He}}/\text{He}$ flux ratio and the two space-borne experiments AMS and Pamela will try to improve upon this by an

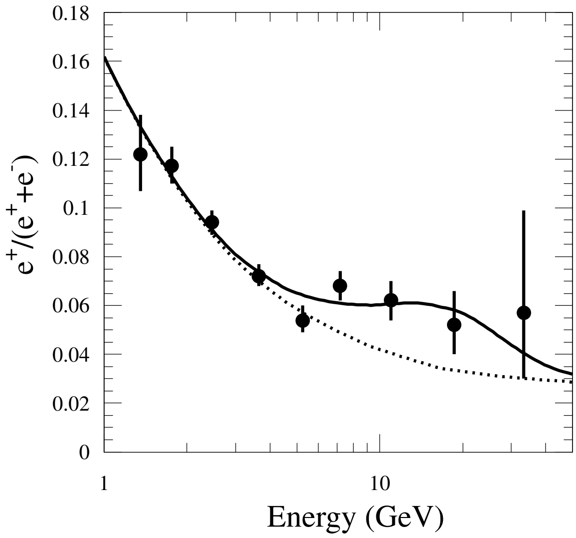

Figure 4. Positron fraction as a function of energy measured by the HEAT experiment (Barwick *et al.*, 1997), predicted under a secondary production hypothesis (*dotted curve*, Moskalenko and Strong, 1998; model 'a' in Figure 3), and predicted for a primary contribution from annihilating dark matter WIMPs (*solid curve*, Coutu *et al.*, 1999).

order of magnitude. However, due to Galactic transport constraints, prospects for a positive detection are essentially non-existent.

During the past decade, dramatic improvements towards the precision measurement of the antiproton flux have been made. The energy region between 200 MeV and 3.5 GeV has been well measured by the BESS collaboration through repeated flights and the observations agree well with calculations of secondary production including the standard Leaky Box model. The collaboration plans to continue their successful program and it is expected that with increased statistics the shape of the low energy spectrum will be better defined. At even lower energies, the observed antiproton flux is strongly affected by solar modulation and, with our present understanding of the solar modulation, it will be difficult to extract a primary low energy $\bar{p}$ contribution. Searches for such a component (for instance from annihilating neutralino dark matter or evaporating black holes) will probably require measurements outside the heliosphere. At energies above a few GeV, recent results hint at an antiproton flux in excess of model predictions. The HEAT-$\bar{p}$ instrument which utilizes multiple energy loss measurements to extend particle identification over a wide energy range (Bower *et al.*, 1999) has been flown and their results will extend the measurements to 50 GeV with sufficient accuracy to determine the spectral behavior of the $\bar{p}/p$ ratio (rise versus fall) within the coming year. Reflights of the HEAT instrument will define the $\bar{p}$ spectrum in the 5–50 GeV region at or above the precision BESS has measured in the 0.2–3 GeV range. At energies above 50 GeV current balloon-borne measurements are limited by atmospheric background and observing time and long-duration balloon (LDB) flights or satellite based instruments become necessary to measure the $\bar{p}$ flux at high energies. The PAMELA satellite experiment which is scheduled to fly in 2005 should be able to perform accurate antiproton measurements over a broad range of energies. It is not entirely inconceivable that with continued access to space and the adoption of proven particle identification techniques, the AMS experiment may add to our current knowledge of antiprotons.

The high proton flux makes positrons notoriously hard to observe but measurements in recent years have succeeded in defining the positron spectrum between 0.1 and 10 GeV. Probably the most exciting result is the discovery by the HEAT group of a possible feature in the positron spectrum at around 7 GeV which can not be explained by a purely secondary production mechanism. A first confirmation of this contribution to the positron spectrum with an independent technique can come as early as this year from the HEAT-$\bar{p}$ instrument. Although primarily designed to measure the $\bar{p}$ spectrum at energies between 5 and 50 GeV, HEAT-$\bar{p}$ will also be able to separate positrons in the energy region of the feature seen by HEAT-$e^{\pm}$. Continued flights of this instrument will not only result in a precise measurement of the positron spectrum in this energy range but will also allow confirmation of the feature and will define its shape. Positron measurements will also be addressed with space borne instruments such as PAMELA in the coming decade.

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References

Adams, F. C., Freese, K., Laughlin, G., Schwadron, N., and Tarlé G.: 1997, *Astrophys. J.* **491**, 6.
Ahlen, S. P., Price, P. B., Salamon, M. H., and Tarlé, G.: 1982, *Astrophys. J.* **260**, 20.
Alcaraz, J. *et al.*: 1999, *Phys. Lett.* **B461**, 387.
Alcaraz, J. *et al.*: 2000, *Phys. Lett.* **B484**, 10.
Barbiellini, G. *et al.*: 1996, *Astron. Astrophys.* **309**, L15.
Barwick, S. W. *et al.*: 1997, *Astrophys. J.* **482**, L191.
Basini, G. *et al.*: 1995, *Proc. 24th Int. Cosmic Ray Conf., Rome* **3**, 1.
Beatty, J. J. *et al.*: 1993, *Astrophys. J.* **413**, 268.
Bergström, D. *et al.*: 2000, *Astrophys. J.* **534**, L177.
Boezio, M. *et al.*: 1997, *Astrophys. J.* **487**, 415.
Boezio, M. *et al.*: 1999, *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City* **3**, 57.
Boezio, M. *et al.*: 2000, *Astrophys. J.* **532**, 653.
Bogomolov, E. A. *et al.*: 1979, *Proc. 16th Int. Cosmic Ray Conf., Kyoto* **1**, 330.
Bogomolov, E. A. *et al.*: 1987, *Proc. 20th Int. Cosmic Ray Conf., Moscow* **2**, 72.
Bogomolov, E. A. *et al.*: 1990, *Proc. 21th Int. Cosmic Ray Conf., Adelaide* **3**, 288.
Bower, C. R. *et al.*: 1999, *Astrophys. J.* **487**, 415; *Proc. 26th Int. Cosmic Ray Conf., Utah* **5**, 13.
Buffington, A., Schindler, S. M., and Pennypacker, C. R.: 1981, *Astrophys. J.* **248**, 1179.

Clem, J. M. *et al.*: 1996, *Astrophys. J.* **464**, 507.
Cohen, A. G., De Rujula, A., and Glashow, S. L.: 1998, *Astrophys. J.* **495**, 539.
Coutu, S. *et al.*: 1999, *Astropart. Phys.* **11**, 429.
Ellis, J. *et al.*: 1988, *Phys. Lett.* **B 214**, 403.
Gaisser, T. K. and Schaeffer, R. K.: 1992, *Astrophys. J.* **394**, 174.
Golden, R. L. *et al.*: 1979, *Phys. Rev. Lett.* **43**, 1264.
Golden, R. L. *et al.*: 1996, *Astrophys. J.* **457**, L103.
Golden, R. L. *et al.*: 1997, *Astrophys. J.* **479**, 992.
Hagelin, J. S. and Kane, G. L.: 1986, *Nucl. Phys.* **B263**, 399.
Hof, M. *et al.*: 1996, *Astrophys. J.* **467**, L33.
Jungman, G. and Kamionkowski, M.: 1994, *Phys. Rev.* **D49**, 2316.
Maeno, T. *et al.*: 2000, *preprint astro-ph/0010381*.
Maki, K., Mitsui, T., and Orito S.: 1996, *Phys. Rev. Lett.* **76**, 3474.
Mitchell, J. W. *et al.*: 1996, *Phys. Rev. Lett.* **76**, 3057.
Moskalenko, I. V. and Strong, A. W.: 1998, *Astrophys. J.* **493**, 694.
Moskalenko, I. V., Strong, A. W., and Reimer, O.: 1998, *Astron. Astrophys.* **338**, L75.
Nozaki, M. *et al.*: 1999, *Proc. 26th Int. Cosmic Ray Conf., Utah* **3**, 85.
Orito, S. *et al.*: 2000, *Phys. Rev. Lett.* **84**, 1078.
Protheroe, R. J.: 1982, *Astrophys. J.* **254**, 391.
Salamon, M. H. *et al.*: 1990, *Astrophys. J.* **349**, 78.
Silk, J. and Srednicki, M.: 1984, *Phys. Rev. Lett.* **53**, 624.
Simon, M., Molnar, A., and Roesler, S.: 1998, *Astrophys. J.* **499**, 250.
Stecker, F. W., Rudaz, S., and Walsh, T. F.: 1985, *Phys. Rev. Lett.* **55**, 2622.
Streitmatter, R. *et al.*: 1990, *Proc. 21st Int. Cosmic Ray Conf., Adelaide* **3**, 277.
Strong, A. W., Moskalenko, I. V., and Reimer, O.: 2000, *Astrophys. J.* **537**, 763.
Webber, W. R. and Pottgieter, M. S.: 1989, *Astrophys. J.* **344**, 779.
Wells, J. D., Moiseev, A., and Ormes, J. F.: 1999, *Astrophys. J.* **518**, 570.