Expected Enhancement of the Primary Antiproton Flux at the
Solar Minimum

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Abstract

We calculate the solar-modulated energy spectra of cosmic-ray antiprotons ($\bar{p}$'s) from two candidate primary sources, i.e., evaporating primordial black holes and the annihilation of neutralino dark matter, as well as for the secondary $\bar{p}$'s produced by cosmic-ray interactions with interstellar gas. A large enhancement toward the solar minimum phase emerges in the low-energy flux of $\bar{p}$'s from the primary sources, whereas the flux of the secondary $\bar{p}$'s, falling steeply below 2 GeV, does not significantly vary. This enables us to conduct a very sensitive search for primary $\bar{p}$ components by precisely measuring the $\bar{p}$ spectrum, especially at low energies, throughout the forthcoming solar minimum phase.

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1 Introduction

Since the discovery of antiprotons ($\bar{p}$’s) in cosmic rays [1, 2, 3], their origin has attracted much interest (for a review, see Ref. [4]). From a standpoint of cosmology and elementary particle physics, it would be of great importance to detect or to set a stringent limit on the primary $\bar{p}$ components from such sources as the annihilation of neutralino dark matter [5, 6, 7, 8], evaporating primordial black holes (PBHs) [9, 10] and superconducting cosmic strings [11]. No evidence for such primary $\bar{p}$ components has been obtained so far.

For the very sensitive search for primary $\bar{p}$’s anticipated in the near future experiments [12], a potential source of background could be the secondary $\bar{p}$’s produced by cosmic-ray interactions with interstellar gas, since the models of the cosmic-ray propagation predict the secondary $\bar{p}$ flux at a level close to the present observations [4, 13, 14, 15, 16]. However, the energy spectra of the primary $\bar{p}$’s are generally expected to be rather soft (i.e., flux increases with decreasing energy), whereas the spectra of the secondary $\bar{p}$’s should steeply fall below 2 GeV due to the kinematics of the $\bar{p}$ production. The signals of the primary $\bar{p}$’s can, therefore, be searched for in the low-energy regions.

In this Letter, we point out that such low-energy portion of the primary $\bar{p}$’s should show a large enhancement toward the solar minimum phase and a rapid decrease afterward, whereas the secondary component, falling steeply below 2 GeV, does not significantly vary. The next solar minimum is expected to arrive in a few years: From the observations of 22-yr solar cycle over the past 45 years by, e.g., the CLIMAX neutron monitor [17], one can expect that the next solar minimum should be arriving in the years 1997 to 1998, which should be followed by a rapid increase of solar activity. The low-energy flux
of the primary $\bar{p}$'s, e.g., those from evaporating PBHs, would increase by a factor of 5 in 1997–1998 as compared to the level in 1993, and would then rapidly decrease by a factor of 15 in 2000. On the other hand, the secondary $\bar{p}$ component shall remain stable within a factor of 1.5 throughout this period. Therefore the extraction of the primary $\bar{p}$ components would become possible with precision measurements of the $\bar{p}$ spectra over the next several years, providing a unique opportunity either to detect or put a stringent limit on the primary $\bar{p}$ components.

2 Evaporating primordial black holes

Primordial black holes (PBHs) may exist as a result of initial density fluctuations, phase transitions, or the collapse of cosmic strings in the early Universe (for a review, see Ref. [18]). Black holes emit particles and evaporate by quantum effects (Hawking radiation) [19]; in particular, PBHs are the only ones with a mass small enough for the quantum emission rate to be significant, possibly producing an observable flux of $\bar{p}$'s [9, 10].

In Ref. [10], we investigated low-energy cosmic-ray $\bar{p}$'s from evaporating PBHs using the Monte Carlo simulation code JETSET 7.4 [20] to obtain the source spectrum of $\bar{p}$'s from PBHs. The local interstellar flux of these $\bar{p}$'s was then calculated using a 3-D Monte Carlo simulation based on the diffusion model of the cosmic-ray propagation. The spatial distribution of PBHs was assumed to be proportional to the isothermal distribution of halo dark mass, i.e., $\rho_h(r) = \rho_{h\odot}(r_{\odot}^2 + r_c^2)/(r^2 + r_c^2)$ [21], where $r$ is the Galactocentric distance with $r_{\odot} = 8.5$ kpc being the position of the Solar system, $r_c = 7.8$ kpc is the core radius, and $\rho_{h\odot} = 0.3$ GeV cm$^{-3}$ is the local halo density. Our 3-D simulation showed
that only PBHs within a few kpc of the Solar system contribute substantially to the local interstellar $\bar{p}$ flux (see also Fig. [1]). We then found that the local PBH explosion rate, $\mathcal{R}$, must be less than $1.7 \times 10^{-2}$ pc$^{-3}$yr$^{-1}$ in order not to conflict with the BESS ’93 data [3]. Nevertheless, we will show later that future experiments can have sensitivity to $\mathcal{R}$ value down to $\sim 1/30$ of the above upper limit. In this Letter, we use the local interstellar $\bar{p}$ flux obtained in Ref. [10] after scaling it for an appropriate value of $\mathcal{R}$.

3 Annihilation of neutralino dark matter

Supersymmetric (SUSY) models for particle physics have been extensively studied in recent years [22]. In most models, the lightest neutralino $\chi$ is taken to be stable and thus serve as cold dark matter (CDM) in the Universe. If the neutralinos comprise the Galactic halo, their annihilation may produce a detectable flux of $\bar{p}$’s [5, 6, 7, 8], since a pair of neutralinos annihilates into quarks, leptons, gauge bosons or Higgs bosons, which then decay or fragment into various particles including $\bar{p}$’s.

Here we study this process in the framework of minimal $N = 1$ supergravity models with radiative breaking of the electroweak gauge symmetry [23]. In this framework, one can calculate all SUSY particle masses and couplings by solving the renormalization group equations with only four SUSY soft breaking parameters: $m_0$, $m_{1/2}$, tan $\beta$ and $A_0$. The higgsino mass parameter $\mu$ is also determined, except for its sign, from the requirement of the electroweak gauge symmetry breaking. We assume $\mu$ to be positive, and the top quark mass to be $m_t = 175$ GeV. Part of the parameter space has already been excluded by theoretical and experimental bounds, including recent results of searches for SUSY
particles at Tevatron 24, 25 and LEP 1.5 26.

We then compute the value of $\Omega_\chi h^2$, where $\Omega_\chi$ is the neutralino relic density in units of the critical density of the Universe and $h$ is the Hubble constant in units of 100 km s$^{-1}$Mpc$^{-1}$. Recently, Berezinsky et al. 27 have pointed out that the expected value of $\Omega_\chi h^2$ falls within the range of $0.2 \pm 0.1$ in most cosmological models from the viewpoint of the age of the Universe. Thus, we choose here four representative parameter sets which give $\Omega_\chi h^2 = 0.18$ (see Table 1). Neutralino dark matter with this value of $\Omega_\chi h^2$ is most likely pure bino, and annihilates predominantly into bottom quarks ($b \bar{b}$) or tau leptons ($\tau^+ \tau^-$).

To obtain the source spectrum of $\bar{p}$'s from the neutralino annihilation, we use the fragmentation functions extracted from JETSET 7.4 20. Since most of the $\bar{p}$'s are produced as the fragments of $b \bar{b}$ (no $\bar{p}$ from $\tau^+ \tau^-$), the shape of their source spectrum does not depend much on the parameter set, although its absolute value scales with $SB_{b\bar{b}}$, where $S$ is the neutralino annihilation rate per unit volume and $B_{b\bar{b}}$ is the branching ratio into $b \bar{b}$. The local interstellar flux of these $\bar{p}$'s is then calculated using a 3-D Monte Carlo simulation based on the diffusion model, as in the case of evaporating PBHs. Note that, whereas the emission rate from evaporating PBHs per unit volume is proportional to their density, $S$ is proportional to the squared neutralino density; thus the local flux of $\bar{p}$'s from the neutralino annihilation is rather sensitive to the halo density distribution.

We will show later that the flux of $\bar{p}$'s from the neutralino annihilation is usually too small to be observed under conventional astrophysical assumptions, i.e., if the neutralino has the homogeneous, spherical and isothermal distribution with $\rho_{h\odot} = 0.3$ GeV cm$^{-3}$. There are, however, at least three astrophysical uncertainties which possibly increase the
\( \bar{p} \) flux by a factor of \( \xi \gg 1 \): First, the Galactic halo may be flattened toward the Galactic disk \[28\]. This shall increase the local halo density \( \rho_{h\odot} \) by a factor of \( \sim 2 \) over that of a spherical halo \[29\], resulting in the enhanced annihilation rate by a factor of \( \xi \sim 4 \). Secondly, a non-dissipative gravitational singularity (NGS) may reside at the Galactic center (GC) \[30\], resulting in the halo density distribution being \( \rho_h(r) = \rho_{h\odot}(r/r_\odot)^{-1.8} \) for \( r \gtrsim 0.1 \) pc. If this is the case, the neutralino annihilation rate would be very high at the GC. Figure 1 shows the \( r \)-distribution of the primary sources (the neutralino annihilation and evaporating PBHs) which contribute to the integrated \( \bar{p} \) flux at the Solar system. It can be seen that, whereas only the annihilation occurring within a few kpc of the Solar system would contribute in the case of the isothermal density distribution, in the NGS model, \( \bar{p} \)'s from the annihilation at the GC would dominate the local interstellar \( \bar{p} \) flux, leading to \( \xi \sim 200 \). Thirdly, high-density CDM clumps with a density enhancement factor of \( 10^2 \)–\( 10^9 \) might be generated in the early Universe \[31\]. If a small portion (a few \%) of neutralino dark matter is in the form of such clumps, the expected \( \bar{p} \) flux could be enhanced by a factor of \( \xi \gtrsim 20 \) \[32\]. Furthermore, if there exists such a clump in the vicinity of the Solar system, the resultant \( \bar{p} \) flux at the Earth could be further enhanced by a large factor.

4 Secondary \( \bar{p} \) flux

When high-energy cosmic rays interact with the interstellar gas, secondary particles are produced including \( \bar{p} \)'s. The expected flux of such secondary \( \bar{p} \)'s was calculated by a number of authors \[4, 13, 14, 15\] who showed that the expected energy spectrum of the
secondary $\bar{p}$’s drops off steeply below 2 GeV. This feature originates from the kinematics of the $\bar{p}$ production, and is independent of the details of the cosmic-ray propagation.

Recently, one of us has calculated the secondary $\bar{p}$ fluxes \cite{ref16} using the two models of the cosmic-ray propagation, i.e., the Standard Leaky Box (SLB) \cite{ref33} and Diffusive Reacceleration (DR) \cite{ref34} models, by taking the most plausible input data such as the parent proton flux. The resultant spectra shown in Fig. 2 have very similar shapes, although the absolute flux in the SLB model is 2.5 times larger than that in the DR model.

5 Solar modulation

When antiprotons go into the Solar system, their energy spectra are changed due to the diffusion, convection, and deceleration processes by the solar wind and the interplanetary magnetic field (solar modulation). The minimal model to describe the processes is the spherically symmetric model \cite{ref36, ref37}, in which all quantities are dependent only on the Heliocentric distance $\varrho$. At the boundary of the Heliosphere ($\varrho = \varrho_b$) the cosmic-ray energy spectrum is assumed to match the interstellar spectrum. The energy spectrum at the Earth ($\varrho = \varrho_E = 1$ AU) can then be calculated by solving the diffusion-convection equation \cite{ref37} using the numerical technique developed by Fisk \cite{ref38}.

As usual, we take the solar wind speed $V = 400$ km/s and the radius of the Heliosphere $\varrho_b = 60$ AU. Since it was shown \cite{ref16} that the spectrum at the Earth is not significantly affected by the position dependence of the diffusion coefficient $\kappa$, we take $\kappa$ to be position-dependent.

\footnote{The interstellar proton flux is taken to be $1.5 \times 10^4 \beta^{-1} P^{-2.74} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$, where $P$ is the momentum in units of GeV, based on the recent observation of the LEAP experiment \cite{ref35}.}
independent and, as normally done, to be proportional to the particle rigidity $R$ as well as to the speed $\beta$, i.e., $\kappa = \beta \kappa_1 R$, where the coefficient $\kappa_1$ varies with solar activity. The solar activity level is then represented by a single parameter: $\phi_F \equiv (\varrho_b - \varrho_E) V/3 \kappa_1$, which roughly corresponds to the “$\phi$ parameter” in the force field approximation \[37\] i.e., the energy loss in the Heliosphere per particle charge. With $\phi_F$ varying between $\sim 350$ and $\sim 1500$ MV from the solar minimum to the maximum, this model reproduces well \[39, 35, 16\] the large variation (a factor of 20) of low-energy proton and helium fluxes as well as each energy spectrum at various stages of solar activity. Since the soft energy spectra of the primary $\bar{p}$’s are similar to those of proton and helium, we use this model of solar modulation to calculate the solar-modulated spectra of the primary $\bar{p}$’s.

To forecast the time variation of $\phi_F$, we can utilize the data of the CLIMAX neutron monitor \[17\], because the $\phi_F$ parameter shows the excellent correlation with the count rate of the neutron monitor \[39\]. The CLIMAX data over the past 45 years clearly show 22-yr solar cycle. Especially the recent trend of the data shows strong similarity to those in $\sim 1950$. From this, one would expect the next solar minimum in the years 1997 to 1998 with the $\phi_F$ parameter reaching $\sim 350$ MV, which should be followed by a rapid increase of solar activity ($\phi_F \sim 1000$ MV) in 2000.

6 Results and discussion

Figure 2 (a) shows examples of the primary $\bar{p}$ fluxes as well as the two secondary $\bar{p}$ fluxes (SLB and DR) solar-modulated with $\phi_F = 350, 550,$ and $1000$ MV, which would corre-
spond to 1997, 1995, and 2000 respectively. The uppermost curves \( \phi_F = 0 \) represent the interstellar spectra. We have taken \( R = 5 \times 10^{-3} \text{ pc}^{-3} \text{yr}^{-1} \) for the \( \bar{p} \) flux from evaporating PBHs, and the case \#1 with \( \xi = 25 \) for the \( \bar{p} \) flux from the neutralino annihilation. It should be noted that the secondary \( \bar{p} \) fluxes are rather insensitive to the solar modulation. This is because the interstellar fluxes decrease with decreasing energy below 2 GeV so that the two effects of the solar modulation, i.e., deceleration and flux suppression cancel each other. Contrastingly, the primary \( \bar{p} \) fluxes would show a large enhancement toward the solar minimum in a very similar way to the proton flux. Note that even the “enhanced” solar minimum fluxes of the primary \( \bar{p} \)’s are very much suppressed as compared to the interstellar fluxes.

Based on the present understanding of the cosmic-ray propagation, we expect that the secondary antiprotons will most likely exist. Therefore, we show in Fig. 2 (b) the solar-modulated \( (\phi_F = 350 \text{ and } 1000 \text{ MV}) \) \( \bar{p} \) fluxes in three cases, i.e., (i) secondary (in the SLB model) only, (ii) secondary (SLB) plus \( \bar{p} \)’s from evaporating PBHs, and (iii) secondary (SLB) plus \( \bar{p} \)’s from the neutralino annihilation. Figure 2 (c) shows the corresponding spectra with the DR model of the secondary \( \bar{p} \)’s.

The unknown absolute intensities of the primary \( \bar{p} \) fluxes \( (R \text{ and } \xi \text{ for PBHs and neutralino dark matter respectively}) \) were chosen here not to conflict with the existing observations. Note that the value of \( R \) taken here (see above) is 1/3 of the upper limit obtained in our previous paper using the BESS ’93 data. Such a weak signal, however, will appear as a striking enhancement of the low-energy \( \bar{p} \) flux at the solar minimum. Also shown is the expected statistical accuracy estimated for a future measurement by the BESS experiment with a total 48-hour flight. As seen in these figures, the existence of
novel primary $\bar{p}$ sources at this level could be detected without any ambiguity. It can also be seen that the signals of the primary $\bar{p}$'s will rapidly diminish after the solar minimum with the increase of solar activity. This strong variation with solar activity would provide further evidence for the primary $\bar{p}$'s, because the spectra of secondary $\bar{p}$'s are not largely affected by the solar modulation.

In the past, the observational data as well as theoretical calculations were usually presented in terms of the $\bar{p}/p$ ratio. However, as shown in Fig. 3, the $\bar{p}/p$ ratio is rather insensitive to the solar modulation of the primary $\bar{p}$'s, since the denominator of proton flux varies in a similar way to the primary $\bar{p}$ components. Therefore, one has to measure the absolute $\bar{p}$ flux and its spectrum in order to fully utilize the characteristic solar modulation of the primary $\bar{p}$'s.

Finally we discuss the attainable sensitivity to the primary $\bar{p}$ components expected in the future experiments. Figure 4 (a) and (b) show the $\bar{p}$ spectra corresponding to Fig. 2 (b) and (c), respectively, for much smaller contributions of the primary $\bar{p}$'s. As seen in the figures, these small signals can also be detected with the expected accuracy. The corresponding sensitivity to the PBH explosion rate $\mathcal{R}$ is $1 \times 10^{-3}$ pc$^{-3}$yr$^{-1}$ in case of the SLB model, and $5 \times 10^{-4}$ pc$^{-3}$yr$^{-1}$ in case of the DR model. These values are respectively 1/17 and 1/34 of the best existing upper limit derived from the BESS '93 data. Note that the explosion rate $\mathcal{R} = 1 \times 10^{-3}$ pc$^{-3}$yr$^{-1}$ is 9 orders of magnitude lower than the upper limit obtained from searches for TeV $\gamma$-ray bursts [41], and is a few hundreds times lower than the upper limit derived from the anisotropy of the diffuse $\gamma$-ray flux [42]. On the standard assumption of the PBH initial mass spectrum [10], this value of $\mathcal{R}$ corresponds to the average PBH density in the Universe of $\Omega_{\text{PBH}} = 3 \times 10^{-10}$, which is a factor of $\sim 30$
below the upper limit deduced from the cosmological diffuse $\gamma$-ray background [43].

Figure 4 also shows that, in order for the $\bar{p}$ flux from the neutralino annihilation to be observable for the case #1, the enhancement factor $\xi$ must be greater than 8 and 4 when the SLB and DR models, respectively, are used for the secondary $\bar{p}$’s. Since such enhancement is possible within astrophysical uncertainties as discussed in Section 3, $\bar{p}$’s from the neutralino annihilation could be observed in the near future.

In conclusion, if future experiments allow us to precisely measure the low-energy cosmic-ray $\bar{p}$ flux at the solar minimum, we should be able to conduct a very sensitive search for primary $\bar{p}$ components by utilizing the characteristic solar modulation of the primary $\bar{p}$’s.

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Figure captions

Figure 1: Distribution (along the Galactocentric distance $r$) of the novel primary sources (the neutralino annihilation and evaporating PBHs) contributing to the integrated $\bar{p}$ flux $F$ at the Solar system, which is located at $r = 8.5$ kpc.

Figure 2: (a) The expected energy spectra of $\bar{p}$'s from evaporating PBHs with $\mathcal{R} = 5 \times 10^{-3}$ pc$^{-3}$yr$^{-1}$ (dashed lines) and from the neutralino annihilation for the case #1 with $\xi = 25$ (dotted lines), as well as the secondary $\bar{p}$'s in the SLB (thick solid lines) and DR (thin solid lines) models. The curves correspond, from top to bottom, to $\phi_F$ values of 0 (interstellar), 350, 550 and 1000 MV. (b) The expected spectra for the secondary $\bar{p}$ (SLB) only (solid lines), secondary $\bar{p}$ (SLB) plus $\bar{p}$'s from evaporating PBHs (dashed lines), and secondary $\bar{p}$ (SLB) plus $\bar{p}$'s from neutralino annihilation (dotted lines). The upper and lower curves correspond to $\phi_F = 350$ and 1000 MV respectively. The normalization parameters for the primary sources are the same as in (a). Also shown is the expected statistical accuracy of a future observation [12]. (c) Same as (b) with the DR model of the secondary $\bar{p}$'s.
Figure 3: The $\bar{p}/p$ ratio corresponding to Fig. 2 (b) and (c). The lower and upper curves correspond to $\phi_F = 350$ and 1000 MV respectively. The proton spectra are obtained by solar-modulating the interstellar spectrum: \(1.5 \times 10^{4} \beta^{-1} P^{-2.74} \text{ m}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{GeV}^{-1}\) \cite{35}, where $P$ is the momentum in units of GeV.

Figure 4: (a) Same as Fig. 2 (b) but for $R = 1 \times 10^{-3} \text{ pc}^{-3} \text{yr}^{-1}$ and $\xi = 8$. (b) Same as Fig. 2 (c) but for $R = 5 \times 10^{-4} \text{ pc}^{-3} \text{yr}^{-1}$ and $\xi = 4$. 
Table 1: Representative sets of SUSY soft breaking parameters (assumed $A_0 = 0$) and relevant quantities derived from them, i.e., (i) the neutralino mass, $m_\chi$; (ii) the mass of the lightest charged SUSY particle (LCSP), $m_{\text{LCSP}}$, together with its identity (chargino $\chi_1^\pm$ or stau $\tilde{\tau}_1$); (iii) the neutralino annihilation rate per unit volume in the local region of the Galactic halo, $S \equiv (\rho_{\chi}\Omega_\chi h^2/\langle \sigma v \rangle_h$, where $\langle \sigma v \rangle_h$ is the thermally-averaged cross section for the neutralino annihilation in the Galactic halo; and (iv) the branching ratio of the neutralino annihilation into bottom quarks, $B_{\bar{b}b}$. Each set gives $\Omega_\chi h^2 = 0.18$. Masses $m_0$, $m_{1/2}$, $m_\chi$ and $m_{\text{LCSP}}$ are shown in units of GeV, $S$ in units of $10^{-32}$ cm$^{-3}$s$^{-1}$, and $B_{\bar{b}b}$ in units of %.

| Set | $m_0$ | $m_{1/2}$ | $\tan \beta$ | $m_\chi$ | $m_{\text{LCSP}}$ | $S$ | $B_{\bar{b}b}$ |
|-----|-------|----------|--------------|----------|-----------------|-----|-------------|
| #1  | 450   | 135      | 40           | 53.6     | 102 ($\chi_1^\pm$) | 32.7 | 96.6        |
| #2  | 191   | 140      | 20           | 54.4     | 101 ($\chi_1^\pm$) | 18.9 | 97.6        |
| #3  | 104   | 224      | 10           | 89.2     | 131 ($\tilde{\tau}_1$) | 0.965 | 43.2        |
| #4  | 107   | 165      | 5            | 62.7     | 117 ($\chi_1^\pm$) | 0.861 | 97.4        |
Fig. 1
Fig. 2

(a) $\phi_F = 0, 350, 550, 1000$ MV

(b) $\phi_F = 350, 1000$ MV

(c) $\phi_F = 350, 1000$ MV

$\overline{\rho}$ Flux ($m^2 \cdot sr^{-1} \cdot s^{-1} \cdot GeV^{-1}$)

Kinetic Energy (GeV)
$\phi_F = 350, 1000 \text{ MV}$

(a) $\text{SLB}$
- $\text{SLB + black holes}$
- $\text{SLB + neutralino}$

(b) $\text{DR}$
- $\text{DR + black holes}$
- $\text{DR + neutralino}$

Fig. 3
\[ \phi_F = 350 \text{ MV} \]

**Fig. 4**

- **SLB**
- **SLB + black holes**
- **SLB + neutralino**

**Kinetic Energy (GeV)**

\[ \text{Flux (m}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{GeV}^{-1}) \]

\[ \phi = 350 \text{ MV} \]