Antiprotons in CR: What Do They Tell Us?

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Abstract

Recent measurements of the CR $\bar{p}$ flux have been shown to pose a problem for conventional propagation models. In particular, models consistent with secondary/primary nuclei ratio in CR produce too few $\bar{p}$'s, while matching the ratio and the $\bar{p}$ flux requires *ad hoc* assumptions. This may indicate an additional local CR component or new phenomena in CR propagation in the Galaxy. We discuss several possibilities which may cause this problem.

1. Introduction

The spectrum and origin of $\bar{p}$'s in CR is of interest for many studies in physics and astrophysics. Most of the observed CR $\bar{p}$'s are "secondaries" produced in collisions of CR particles with interstellar gas. Their spectrum with a peak at about 2 GeV is distinctly different from other CR species. Some proportion of the $\bar{p}$'s might originate in WIMP annihilations and/or primordial black hole evaporation contributing mostly at low energies. During the last decade there have been a number of space and balloon CR experiments with improved sensivity and statistics, which impose stricter constraints on the models of CR propagation and heliospheric modulation. It has been recently shown [5] that accurate $\bar{p}$ measurements during the last solar minimum 1995-97 [8] indicate a discrepancy with calculations made using existing propagation models. Because of the specific shape of the secondary $\bar{p}$ spectrum and the fact that their production in the ISM can be calculated accurately, $\bar{p}$'s provide a unique opportunity to test models of CR propagation and heliospheric modulation.

2. The Problem

Secondary $\bar{p}$'s, e^+'s, and some proportion of diffuse γ-rays are products of interactions of mostly CR protons and He nuclei with interstellar gas. In very much the same way spallation of CR nuclei give rise to secondary isotopes. Propagation

of all particles is governed by the same mechanism. The main constituents are diffusion, energy losses and gains, particle production and disintegration. Because the mechanism is the same for *all* particles, a correct CR propagation model that describes any secondary to primary ratio should equally well describe all the others: B/C, sub-Fe/Fe, $\bar{p}/p$ ratios, and spectra of nuclei, e^+'s, and diffuse continuum γ-rays.

The diffusive reacceleration models have certain advantages compared to other CR propagation models: they naturally reproduce secondary/primary nuclei ratios in CR, have only three free parameters (normalization and index of the diffusion coefficient, and the Alfvèn speed), and agree better with K-capture parent/daughter nuclei ratio [3]. However, the reacceleration models designed to match the nuclei ratios produce too few $\bar{p}$'s [5] because matching the B/C ratio at all energies requires the diffusion coefficient to be too large. The discrepancy is ~40% at 2 GeV while the stated uncertainty in measured $\bar{p}$ flux in this energy range is now ~20%. The conventional models without reacceleration based on local CR measurements, with simple energy dependence of the diffusion coefficient, and with uniform CR source spectra throughout the Galaxy also fail to reproduce simultaneously both the B/C ratio and $\bar{p}$ flux.

The difficulty associated with $\bar{p}$'s may indicate new effects, if new experiments can confirm the BESS measurements.

3. Discussion of Uncertainties

The sources of uncertainties which may affect the interpretation of $\bar{p}$ measurements appear to be fourfold: (i) propagation models and parameters, (ii) heliospheric modulation, (iii) production cross sections of secondary nuclei and $\bar{p}$'s, and (iv) systematic measurement errors.

(i) To this category we attribute errors in the Galactic gas distribution, ambient spectrum of CR, and our current knowledge of CR diffusion process. ◊ The errors in the gas distribution appear not to be so important in the case of stable and long-lived nuclei. Such errors are compensated simultaneously for all species by the corresponding adjustment of the propagation parameters. ◊ The local interstellar CR spectrum is studied quite well by direct measurements at HE where solar modulation effects are minimal, while the ambient CR proton spectrum on the large scale remains unknown. The most direct test is provided by diffuse γ-rays, but here we have a well known puzzle of the GeV excess in the EGRET data [2]. A possible explanation is the inverse Compton scattering (ICS) of electrons whose Galactic spectrum may be harder than the local one [9]; an explanation justified by the large electron energy losses. ◊ Our understanding of the CR propagation in the Galaxy is quite basic. The distribution of CR sources is uneven in space and random in time. The diffusion is assumed *ad hoc* to be governed by one unique mechanism over the decades of energy MeV-PeV, while

the diffusion coefficient is often taken the same for the whole Galaxy. It is certainly an approximation, but in fact most of CR data (except $\bar{p}$'s) support it.

(ii) Heliospheric modulation may introduce some error; it will be similar for all CR nuclei which have the charge/mass ratio about $+1/2$, except (anti-) protons which have ± 1. Besides, solar modulation for $\bar{p}$'s is different from that of protons, due to charge sign dependent drift effects in the heliosphere. At present, several spacecraft provide information about particle fluxes at different heliolatitudes (Ulysses) and close to the heliospheric boundary (Voyagers), which make the likelihood of a serious error small. However, if modulation is weaker than assumed a reacceleration model combining B/C, $\bar{p}$'s, and other CR species is feasible.

(iii) Nuclear cross section errors are one of the main concerns. $\diamondsuit$ Fitting B/C ratio in CR is a standard procedure to derive the propagation parameters, while the calculated ratio, in turn, depends on the total interaction and isotope production cross sections. The latter have large uncertainties, typically $\gtrsim 20\%$, and sometimes larger. In our calculations we use our own *fits to the data* on cross sections $p + \mathrm{C, N, O} \rightarrow \mathrm{Be, B}$, that produce most of the Be and B (see [7]). We thus can rule out a possibility of large errors in the calculated B/C ratio. $\diamondsuit$ Antiproton production cross section in pp-interactions is studied quite well, while $\bar{p}$ production on nuclei relies on scarce data. This may lead to underestimation of the atmospheric contribution to the $\bar{p}$ flux measured in the upper atmosphere. The flux of CR $\bar{p}$'s thus may be *lower* at the top of the atmosphere by $\sim$25–30% [1], giving better agreement with our calculations in the reacceleration model. An analysis of different parametrizations of $\bar{p}$ production on nuclei is given in [4].

(iv) Systematic measurement errors are difficult to account for, but their effect can be reduced by careful choice of the data. The $\bar{p}$ data we rely on is the flux at maximum $\sim$2 GeV where the statistical errors are minimal. The spectra of protons and He are measured almost simultaneously and quite precisely by BESS and AMS (see [5]). They also agree with earlier experiments within the error bars. The most accurate measurements of nuclei at low energies are made by ACE, Ulysses, and Voyager and the agreement is good. At HE the data obtained by HEAO-3 are the most accurate and generally agree with earlier measurements; we compare with the data in the middle of the interval where the systematic errors should be minimal. However, new HE CR measurements are desirable.

4.   Alternative Possibilities

A solution in terms of propagation models requires a break in the diffusion coefficient at a few GV [5]. It has been interpreted as change in the propagation mode; propagation of LE particles may be aligned to the magnetic field lines rather than scattering. The chaotic distribution of the magnetic field gives it a diffusion-like character.

If our local environment influences the spectrum of CR, then it is possible

to solve the problem by invoking a fresh "unprocessed" nuclei component at LE [6], which may be produced in the Local Bubble. The idea is that primary CR like C and O have a local LE component, while secondary CR like B are produced Galaxy-wide over the confinement time of 10–100 Myr. In this way an excess of B, which appears when propagation parameters are tuned to match the $\bar{p}$ data, can be eliminated by an additional local C (and the reduced Galactic production of B). The model appears to be able to describe a variety of CR data, but at the price of additional parameters.

A consistent $\bar{p}$ flux in reacceleration models can be obtained if there are sources of LE protons $\lesssim$20 GeV. This energy is above the $\bar{p}$ production threshold and effectively produces $\bar{p}$'s at $\lesssim$2 GeV. The intensity and spectral shape of this component could be derived by combining restrictions from $\bar{p}$'s and diffuse γ-rays. This kind of nucleon spectrum was used in our HEMN model [9] to match the spectrum of diffuse γ-rays as observed by EGRET [2].

More $\bar{p}$'s may be produced if there is a population of hard-nucleon-spectrum sources in the inner Galaxy. Such a population is required since the ICS of hard-spectrum electrons is insufficient to obtain an acceptable fit to the diffuse γ-ray latitude profiles [10]. Antiprotons produced by freshly accelerated particles in matter near the source can add up to $\bar{p}$'s produced Galaxy-wide. We are going to address this possibility in future.

To summarize, it is clear that accurate measurements of $\bar{p}$ flux are the key to testing current propagation models. If new measurements confirm the $\bar{p}$ "excess," current propagation and/or modulation models will face a challenge. If not – it will be evidence that reacceleration model is currently the best one to describe the data.

5. References

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