A Combined Interpretation of Cosmic Ray Nuclei and Antiproton High Energy Measurements

Carmelo Evoli*, **Daniele Gaggero**†‡, **Dario Grasso**† **and Luca Maccione**§

*SISSA/International School for Advanced Studies, via Beirut, 2-4, I-34014 Trieste, Italy.
†INFN, Sezione di Pisa, Largo B. Pontecorvo, 3, I-56127 Pisa, Italy.
‡Dipartimento di Fisica "E. Fermi", Università di Pisa, Largo B. Pontecorvo, 3, I-56127 Pisa, Italy.
§DESY, Theory Group, Notkestrasse 85, D-22607 Hamburg, Germany

***Abstract*. In the last months several ballon and satellite experiments improved significantly our knowledge of cosmic ray (CR) spectra at high energy. In particular CREAM allowed to measure B/C, C/O and N/O ratios up to 1 TeV/n and PAMELA the $\bar{p}/p$ ratio up to 100 GeV with unprecedented accuracy. These measurements offer a valuable probe of CR propagation properties. We performed a statistical analysis to test the compatibility of these results, as well as other most significant experimental data, with the predictions of a new numerical CR diffusion package (DRAGON). We found that above 1 GeV/n all data are consistent with a plain diffusion scenario and point to well defined ranges for the normalization and energy dependence of the diffusion coefficient.**

***Keywords*: cosmic rays, propagation model, statistical analysis.**

I. Introduction

The problems of origin and propagation of Cosmic Rays (CR) in the Galaxy are long standing questions which need the combination of several different observations in a wide energy range to be answered [1].

The most realistic description of CR propagation is given by diffusion models. Two main approaches have been developed so far: (semi-)analytical diffusion models (see e.g. [2] and ref.s therein), which solve the CR transport equation by assuming simplified distributions for the sources and the interstellar gas, and fully numerical diffusion models. Well known realizations of those two approaches are respectively the *two-zone model* [3], [4] and the GALPROP [5], [6], [7] and DRAGON [8] codes. Generally these models involve a large number of parameters which need to be fixed against the observations. Their knowledge is crucial not only for CR physics but also to be able to constrain/determine the properties of dark matter from indirect measurements. However, in spite of the strong efforts made on both observational and theoretical sides most of those parameters are still poorly known. One of the reasons lies in the fact that best quality data on CR spectra were available mainly at low energy ($\lesssim 10$ GeV/n). At these energies several competing physical processes (e.g. solar modulation, convection, re-acceleration) are expected to affect significantly the CR spectra to an *a priori* unknown amount. Furthermore, at those energies uncertainties in spallation cross section determinations are still sizeable. At higher energies, however, only spatial diffusion and spallation losses are expected to shape the CR spectra, the latter effect becoming less relevant with increasing energy. Hence, the study of high energy CR spectra could allow to constrain the properties of the diffusion coefficient of CR in the Galaxy.

The scarcity of observational data has precluded this possibility for long time. The situation improved recently as the CREAM balloon experiment [9] measured the relative abundances of elements from boron to oxygen, and especially the boron to carbon ratio (B/C), up to energies around 1 TeV/n. Furthermore, valuable complementary data were recently provided by the PAMELA satellite experiment [10] which measured the antiproton/proton ($\bar{p}/p$) ratio up to 100 GeV with unprecedented accuracy. Also antiprotons are expected to be produced by the spallation of primary CRs (mainly protons and Helium nuclei). They provide, therefore, an independent test of the validity of CR propagation models [11], [12] and, once these are validated, a valuable probe of dark matter models (see e.g. [13]).

In this contribution we show that the data recently released by the CREAM and the PAMELA experiments can fit into a unique plain diffusion (PD) CR propagation model. We report the main results of a statistical analysis aimed at constraining the normalization and energy dependence of the diffusion coefficient of CRs in the Galaxy. In order to check the possible dependence on low energy effects of these constraints, we also study as they change by varying the minimum energy $E_{\rm min}$ above which data are considered.

II. Model

In order to interpret the experimental data we need to adopt a theoretical model describing the propagation of CR nuclei in the Galaxy between 1 and 10^3 GeV/n. At these energies, the propagation of stable CRs is known to obey the transport equation [14]

$$\frac{\partial N_i}{\partial t} = -\nabla \cdot (\mathbf{D} \cdot \nabla N_i) + Q_i(E_k) + \\ - c\,\beta\, n_{\rm gas}\, \sigma_{\rm in}(E_k) N_i + \sum_{j>i} c\,\beta\, n_{\rm gas}\, \sigma_{ji} N_j \;, \quad (1)$$

where $E_k \equiv (E - m_A)/A$ (E is the total energy of a nucleus with mass $m_A \simeq A \times m_{\rm pr}$) is the kinetic energy per nucleon, constant during propagation as practically conserved in fragmentation reactions, β is the velocity of the nucleus in units of the speed of light c, σ_i is the total inelastic cross section onto the ISM gas with density $n_{\rm gas}(r, z)$ and σ_{ij} is the production cross-section of a nuclear species j by the fragmentation of the i-th one. We start the spallation routine from $A = 64$. We disregard continuos energy losses, re-acceleration and convection, but we check *a posteriori* the validity of this approximation against the experimental data.

We solve Eq. (1) in the stationary limit $\partial N_i/\partial t = 0$ adopting our numerical code DRAGON [8]. DRAGON was validated against well known public codes (GALPROP) and against experimental data of secondary/primary ratios, as well as γ-ray data.

We recall below the main assumptions we make.

A. Spatial diffusion

We assume cylindrical symmetry and that the regular magnetic field is azimuthally oriented ($\mathbf{B_0} = B_\phi(r, z)\,\hat{\phi}$). Under these conditions CR diffusion out of the Galaxy takes place only perpendicularly to $\mathbf{B_0}$. Therefore D represents in fact the perpendicular diffusion coefficient $D_\perp$. The dependence of D on the particle rigidity ρ is (see e.g. [15])

$$D(\rho, r, z) = D_0\ \beta \left(\frac{\rho}{\rho_0}\right)^\delta \quad \exp\{|z|/z_t\}\ . \qquad (2)$$

B. CR sources

For the source term we assume the general form

$$Q_i(E_k, r, z) = f_S(r, z)\ q_0^i\ \left(\frac{\rho}{\rho_0}\right)^{-\alpha_i}\ , \qquad (3)$$

imposing $Q_i(E_k, r_\odot, z_\odot) = 1$.

We assume that the CR source spatial distribution $f_S(r, z)$ trace that of Galactic supernova remnants (SNRs) as modeled in [16] on the basis of pulsar and progenitor star surveys [17].

The injection abundances q_0^i are tuned so that the propagated spectra of primary and secondary species match the observed ones.

For each value of δ in Eq. (2) α_i is fixed by the requirement that at high energy $E_k \gg 100$ GeV/n, at which spallation processes are almost irrelevant, the equality $\alpha + \delta = 2.7$ is satisfied[1].

III. Analysis and results

Since our main goal is to understand in particular the diffusion properties, we want derive constraints on D_0, δ and z_t in Eq. (2). We consider these observables: N/O, C/O, B/C and $\bar{p}/p$ ratios. They are primary/primary and secondary/primary ratios. The spectrum of secondary/primary ratios allows us to infer information directly on δ [2], but not separately on D_0 and z_t (these observables are sensitive to the ratio D_0/z_t [8]). A way to break this degeneracy is to consider unstable to stable ratios (e.g. ^{10}Be/^{9}Be), which are known to probe the vertical height of the Galaxy [2]. In agreement with [8], [18] we infer that z_t should lie between 3 and 5 kpc. We account for a solar modulation potential $\Phi = 550$ MeV in the "force-free" approximation [19].

A. Strategy

1) B/C ratio: Once the spatial distributions of the CR sources and the ISM gas have been chosen, the main parameters determining the B/C in a PD model are the C/O and N/O injection ratios and the quantities δ and D_0/z_t (which will be always expressed in units of 10^{28} cm^2 s^{-1} kpc^{-1} in this work) in Eq. (2).

We fix the source abundances of the oxygen and of primaries heavier than oxygen by requiring that they match the observed abundances in CRs at $E \sim 1 - 10$ GeV/n, while we use primary/primary ratios to fix the C/O and N/O[2] injection ratios.

As in [8], we accomplish this by sampling, for each pair (D_0/z_t, δ), the parameter space (C/O, N/O) and computing the χ^2 of our predictions for the C/O and N/O modulated ratios against experimental data over the energy range of our interest. For the set of parameters that minimizes this χ^2, we then compute the χ^2 (which we call $\chi^2_{\rm B/C}$) of our predictions for the B/C ratio against data. By iterating this procedure for several values of the pair (D_0/z_t, δ), we sample the whole parameter space of our interest. Minimization of $\chi^2_{\rm B/C}$ leads to the best fit values for ($D_0/z_t, \delta$) and the appropriate confidence regions.

2) Antiprotons: The construction of a statistically meaningful variable for the $\bar{p}/p$ ratio is rather simpler than for the B/C. Indeed, if we neglect the systematic uncertainties associated to the production and interaction cross sections, the propagation of secondary antiprotons depends essentially on D_0/z_t, δ and the source abundance ratio He/p. This last unknown can be easily fixed by looking at the measured spectrum of He at Earth, which is relatively well known. Therefore, we construct a $\chi^2_{\bar{p}/p}$ by comparing our predicted $\bar{p}/p$ spectrum for different values of ($D_0/z_t, \delta$) to experimental observations.

3) Joint comparison: Since we have two different data-sets for the same physical framework, it is important to find links for joint optmization of the combined analysis. The two data-sets being uncorrelated, it is possible to define a joint χ^2 knowing the single results of the previous analysis

$$\chi^2 = \frac{1}{2}\left(\chi^2_{B/C} + \chi^2_{\bar{p}/p}\right) \qquad (4)$$

and minimize it with respect to ($D_0/z_t, \delta$).

[1]In this regime, the theoretical expectation for the observed flux Φ on Earth is $\Phi(E) \approx Q(E)/D(E) \sim E^{-(\alpha+\delta)}$ [2].

[2]Note that N = ^{14}N + ^{15}N is a combination of primary and secondary nuclides.

The complementary nature of the two data sets will be demonstrated in section III-C in which the overlapping of the separated analysis is evident.

B. Experimental Data

So far the best B/C measurements above $1\ \mathrm{GeV/n}$ have been provided by the HEAO-3 [20] and CRN [21] experiments in the range $1 < E_k < 30\ \mathrm{GeV/n}$ and $70\ \mathrm{GeV/n} < E_k \lesssim 1.1\ \mathrm{TeV/n}$. Recently, the CREAM [9] experiment has released data [22] improving significantly the available statistics at high energy. C/O and N/O data are taken from the same experiments as well.

For antiprotons we use experimental data released by BESS for the periods 1995-97 [23] and 1998 [24] in the energy interval $1-4\ \mathrm{GeV}$, and by CAPRICE (1998) [25] in the range $3-49\ \mathrm{GeV}$. Recently also the PAMELA experiment has released $\bar{p}/p$ data in the energy range $1-100\ \mathrm{GeV}$ [10]. We include them in our analysis.

Solar modulation has been demonstrated to have important effects in the determination of the $\bar{p}/p$ ratio at low energy. We account for modulation in the force free approximation. For each data set we use the solar potential of the year when data were taken.

C. Results

In Fig. 1 we show our results for the separated and joint analysis of the B/C and $\bar{p}/p$ data. The left-hand plots represent the 1, 2 and 3σ contour levels of the $\chi^2_{\mathrm{B/C}}$, in the $(D_0/z_t, \delta)$ space, the central plots show the same contour levels for $\chi^2_{\bar{p}/p}$, while the right-hand side plot is the result of the joint analysis described in section III-A3[3]. From the panels in the first column the impact of CREAM results on our knowledge of the propagation parameters is evident: CREAM high energy data favour a smaller value of δ with respect to previous ones. Also PAMELA $\bar{p}/p$ data are sensitive to our propagation parameters, in contrast with pre-PAMELA $\bar{p}/p$ data (see the upper row panels in Fig. 1). Finally, it is clear from the lower row panels as for $E_{\min} > 5\ \mathrm{GeV}$ there is an almost complete concordance between the CL regions constrained by high energy B/C and $\bar{p}/p$ data. Indeed, even the 1σ regions do have a significant overlapping and the minimum joint χ^2 is 1.2 for $E_{\min} = 6\ \mathrm{GeV/n}$. The joint analysis indicates a best-fit value of $\delta \lesssim 0.5$, possibly favouring a Kraichnan power spectrum for the turbulent galactic magnetic field. While the best fit for δ seems not to be strongly dependent on $E_{\min}$, we find that the best value of D_0/z_t tends to be larger when a larger $E_{\min}$ is considered. This could indicate, in agreement with naïve expectations, that the scale of vertical diffusion z_t is smaller at higher energies.

The concordance between nuclear and antiproton data is also evident from Fig. 2 where the predictions of the combined analysis best-fit model are compared with B/C and $\bar{p}/p$ experimental data.

Finally, in Tab. I we recap the findings of our minimization strategy. Best fit values for $(D_0/z_t, \delta)$ are obtained considering first the two data sets separetely and then jointly.

Our analysis shows clearly that the two data sets are statistically compatible, within our model.

[3]Our χ^2 variables are always understood to be "reduced" χ^2.

IV. Conclusions

We performed a statistical analysis to constrain the CR propagation parameters in a plain diffusion scenario numerically implemented in DRAGON. Taking advantage of the new CREAM and PAMELA high-energy data we performed a combined analysis of B/C and $\bar{p}/p$ data in several energy ranges. This approach allowed us to test the (weak) dependence of our results on poorly know low-energy physics. We showed that above few GeV/n the whole data sets considered here are consistently reproduced by a PD model. Our findings favour a Kraichnan type ($\delta \simeq 0.5$) dependence of the diffusion coefficient on energy.

References

[1] Strong A W, Moskalenko I V and Ptuskin V S, 2007 *Ann. Rev. Nucl. Part. Sci.* **57** 285 [arXiv:astro-ph/0701517]

[2] Berezinsky V S *et al.*, Astrophysics of Cosmic Rays, North-Holland, 1990

[3] Maurin D, Donato F, Taillet R and Salati P, 2001 *Astrophys. J.* **555** 585 [arXiv:astro-ph/0101231]

[4] Maurin D, Taillet R and Donato F, 2002 *Astron. Astrophys.* **394** 1039 [arXiv:astro-ph/0206286].

[5] Strong A W and Moskalenko I W, 1998 *Astrophys. J.* **509** 212 [arXiv:astro-ph/9807150]

[6] Strong A W, Moskalenko I V and Reimer O, 2004 *Astrophys. J.* **613** 962 [arXiv:astro-ph/0406254]

[7] GALPROP project web page: http://galprop.stanford.edu/web_galprop/galprop_home.html

[8] Evoli C, Gaggero D, Grasso D and Maccione L, JCAP **0810** (2008) 018 [arXiv:0807.4730].

[9] Ahn H S et al. [CREAM collaboration], 2008 *Astropaticle Physics* **30** 133

[10] Adriani O et al. [PAMELA collaboration], 2009 *Phys. Rev. Lett.* **102** 051101

[11] Donato F, Maurin D, Salati P, Barrau A, Boudoul G and Taillet R, 2001 *Astrophys. J.* **563** 172 [arXiv:astro-ph/0103150]

[12] Moskalenko I V, Strong A W, Ormes J F and Mashnik S G, 2005 *Advances in Space Research* **35** 156 [arXiv:astro-ph/0301450]

[13] Donato F, Maurin D, Brun P, Delahaye T and Salati P, 2009 *Phys. Rev. Lett.* **102** 071301 [arXiv:0810.5292]

[14] Ginzburg V L and Syrovatskii S I, "The Origin of Cosmic Rays", New York, MacMillan, 1964

[15] Ptuskin V S et al., 1997 *Astron. Astrophys.* **321** 434

[16] Ferrière K M, 2001 *Rev. of Mod. Phys.* **73** 1031 [arXiv:astro-ph/0106359]

[17] Evoli C, Grasso D and Maccione L, 2007 *JCAP* **0706** 003 [arXiv:astro-ph/0701856]

[18] Moskalenko I V, Mashnik S G and Strong A W, *Proceedings of "27th International Cosmic Ray Conferences (ICRC 2001), Hamburg, Germany, 7-15 Aug 2001"* [arXiv:astro-ph/0106502]

[19] Gleeson L J and Axford W I, 1968 *Astrophys. J.* **154** 1011

[20] Binns W R et al. [HEAO-3 Collaboration], 1989 *Astrophys. J.* **346** 997

[21] Swordy P S et al., 1990 *Astrophys. J.* **349** 625

[22] H. S. Ahn *et al.*, Astropart. Phys. **30** (2008) 133 [arXiv:0808.1718 [astro-ph]].

[23] Orito S et al. [BESS Collaboration], 2000 *Phys. Rev. Lett.* **84** 1078 [arXiv:astro-ph/9906426]

[24] Maeno T et al. [BESS Collaboration], 2001 *Astropart. Phys.* **16** 121 [arXiv:astro-ph/0010381]

[25] Boezio M et al. [WiZard/CAPRICE Collaboration], 2001 *Astrophys. J.* **561** 787 [arXiv:astro-ph/0103513]

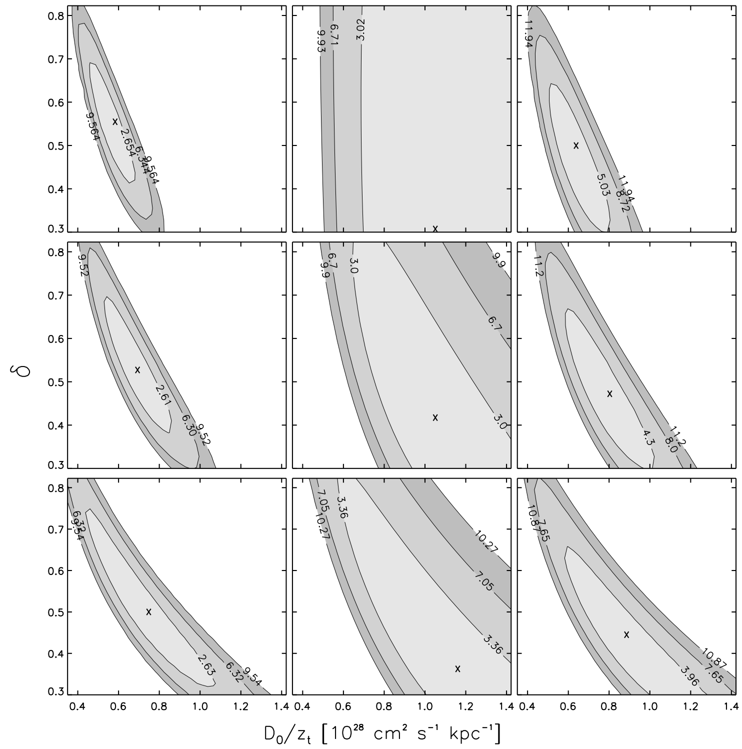

Fig. 1. 1, 2 and 3σ CL regions for different data sets. The left-hand plots represent the CL of $\chi^2_{\rm B/C}$, the central plots show the same CL for $\chi^2_{\bar{p}/p}$, while the right-hand side plot is the result of the joint analysis. The top panel is obtained for $E_{\rm min} = 1$ GeV/n and with all data before CREAM and PAMELA, the central one for $E_{\rm min} = 1$ GeV/n and all data while the bottom panel is for $E_{\rm min} = 5$ GeV/n and all data.

TABLE I
RESULTS OF THE STATISTICAL ANALYSIS DESCRIBED IN SEC. III.

	Min $\chi^2(B/C)$			Min $\chi^2(\bar{p}/p)$			Joint analysis		
Emin	D_0/z_t	δ	χ^2	D_0/z_t	δ	χ^2	D_0/z_t	δ	χ^2
1	0.68	0.52	0.39	1.04	0.41	0.84	0.76	0.47	1.94
5	0.74	0.49	0.33	1.15	0.36	1.06	0.87	0.44	1.66
10	0.82	0.47	0.22	0.82	0.52	1.22	0.87	0.44	0.88

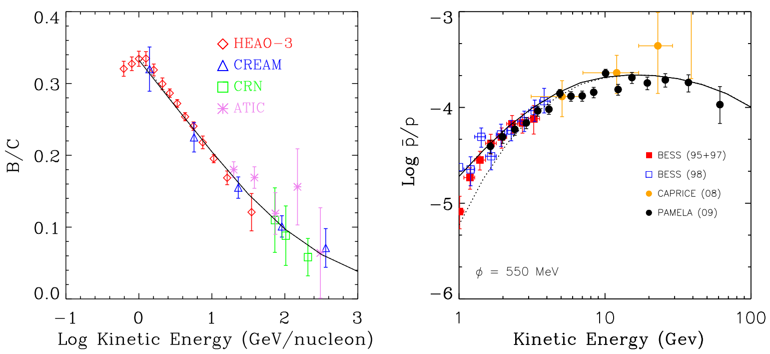

Fig. 2. Comparison of experimental (top of the atmosphere) data for B/C (left panel) and $\bar{p}/p$ ratios with our joint analysis best-fit model (second row in Tab. I). Dotted lines refer to LIS ratios, accounting for solar modulation with potential $\phi = 550$ MV.