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A unified picture for three different cosmic-ray observables

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We present here a unified scenario that connects together three peculiar spectral features recently reported in the spectra of charged cosmic rays (CRs). The hadronic spectral hardening above ~ 250 GV is here interpreted as a diffusion imprint, and modeled by means of a transport coefficient that smoothly hardens with rigidity. We implement such a propagation framework to solve the transport equation with the DRAGON2 numerical code in order to determine the large-scale contribution to the CR fluxes. On top of this solution we explore the hypothesis of a nearby, hidden Supernova Remnant (SNR) to be responsible for the high-energy (above $\sim$ 100 GeV) all-lepton flux, in particular for the spectral break observed around 1 TeV. We compute such contribution analytically adopting the same propagation setup implemented for the large-scale background. Simultaneously, we find the signature of the same source in the peculiar *bump* structure observed by the DAMPE Collaboration in the proton spectrum, consisting of a strong hardening at $\sim$ 500 GeV and a softening at 13 TeV. We validate our hypothesis with the CR dipole-anisotropy (DA) amplitude and phase, and find that the observations below $\sim$ 10 TeV can be considered as a signature of the nearby SNR that we invoke. If confirmed, our modelling strongly constrains the propagation parameters of the charged particles in our Galaxy and sets the ground for the understanding of the high-energy γ-ray observations of the forthcoming years.

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1. Introduction

A dramatic improvement in the accuracy of cosmic-ray (CR) measurements has been recently achieved, which offer a unique opportunity to shed light on several long-standing key questions about galactic CR physics [1]. In particular, the AMS-02 Collaboration recently reported the absolute fluxes of light nuclear species [2, 3] and pointed out a progressive spectral hardening at high rigidities ($\sim 250\,\mathrm{GV}$). This feature is twice as large in the secondary species [4], suggesting a diffusive origin. The DAMPE experiment confirmed this spectral break in the proton spectrum and also observed a softening at 13.6 TeV [5]. Such structured feature may be the signature of a nearby CR accelerator. Attempts to reconcile the CR fluxes with the dipole anisotropy involve a anomalously slow diffusivity around the sources [6] and/or a two-zone diffusion *only* applied to the background particles [7], and either way with no connection with the leptonic spectrum.

The H.E.S.S. [8], CALET [9] and DAMPE [10] collaborations measured a break at 1 TeV in the all-lepton spectrum, which could be a signature of a local source. As discussed in [11], this source should not produce electrons and positrons in similar amounts, to be compatible with the observed positron fraction: a nearby Supernova Remnant (SNR) would hence fulfill this requirements. However, no known SNR has been found to be a suitable candidate.

Here we propose a comprehensive scenario that simultaneously explains the bump in the CR spectrum, the all-electron spectrum and the dipole anisotropy. This model is based on the following arguments: (i) We argue that a nearby fading SNR is associated to both the hadronic *bump* measured by DAMPE and the $\sim$ 1 TeV break in the all-lepton spectrum. (ii) We adopt a transport scenario featuring a scaling that progressively hardens with increasing energy, motivated by AMS-02 data. We show that this is essential to satisfy the constraints imposed by the measured anisotropy.

2. The transport setup

In this section we describe the propagation setup that will be used throughout the paper. We refer to the publication [12] (hereafter F21b) for a more extensive description. We consider two distinct populations of CRs: (i) a diffuse large-scale background of hadronic and leptonic species, (ii) an extra contribution from a nearby accelerator. The propagation of the first population is computed by solving the general diffusion-loss transport equation with the `DRAGON`[1] [13] package. We calculate the contribution from the second population by solving the following (reduced) transport equation:

$$\frac{\partial f(E,t,r)}{\partial t} = \frac{D(E)}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial f}{\partial r} + \frac{\partial}{\partial E}(b(E)f) + Q(E,t,r), \tag{1}$$

where $Q(E,t,r) = S(E)L(t)\delta(r)$ considers a time-dependent injection, $D(E) = D_0\left(\frac{E}{E_0}\right)^{\delta(E)}$ and the loss term, $b(E) = -\frac{4}{3}\,c\sigma_{\mathrm{T}}\left[f^i_{\mathrm{KN}}U_i + U_B\right]\left(\frac{E}{m_e c^2}\right)^2$, includes the Klein-Nishina (KN) relativistic correction to the Inverse Compton (IC) cross-section, as discussed in [14]. The details of the terms and the calculation to solve Equation (1) are presented in F21b.

The key difference with respect to previous studies resides in the *transport setup*, characterized by an energy-dependent slope, $\delta(E)$, of the diffusion coefficient, for both the smooth large-scale

[1] https://github.com/cosmicrays/DRAGON

component and the extra contribution. In particular, motivated by the analyses on secondary/primary ratio measured by AMS-02, we adopt the phenomenological setup considered in [15]. In that scenario the diffusion coefficient, which is commonly parametrized as $D(E) = D_0 \left(\frac{E}{E_0}\right)^{\delta(E)}$ (with D_0 normalization at reference energy E_0), smoothly hardens as rigidity increases:

$$\frac{d \log D(\rho)}{d \log \rho} \equiv \gamma(\rho) \approx \gamma_{\rm high} + \frac{\Delta}{1 + \frac{\xi}{1-\xi}\left(\frac{\rho}{\rho_0}\right)^{\Delta}}, \tag{2}$$

where $\rho = E/Ze$ is the particle rigidity, ρ_0 is its reference, and $(\gamma_{\rm high}, \Delta, \xi)$ are free parameters.

Slightly modifying the THMb model described in [15] for the updated datapoints, the reference values of the parameters are: $\gamma_{\rm high} = 0.19$, $\Delta = 0.53$, $\xi = 0.1$, with $D_0 = 1.21 \cdot 10^{28}\,{\rm cm^2\,s^{-1}}$ at reference rigidity 2 GV. Accordingly, the diffusion coefficient scales as $\sim E^{0.67}$ in the lowest-energy region ($E \sim 1$ GeV) and hardens up to $\sim E^{0.20}$ at the highest energies ($E > 10^4$ GeV), exhibiting a smooth transition. In [15] it is shown that such a setup is formally equivalent to a two-zone transport model where the properties of the interstellar medium (ISM) change between an inner-halo ($|z| < \xi L$) and an extended-halo ($\xi L < |z| < L$), where $L \sim 4$ kpc and $\xi \sim \mathcal{O}(0.1)$.

In this work, the transport setup described in Equation (2) is adopted consistently in both the large-scale propagation and in the propagation of particles from the nearby remnant.

3. A consistent picture of electron, proton and anisotropy data

Based on the rate of SN events in the Galaxy [16] and on the leptonic losses, we find (see F21b) that it is reasonable to consider only one nearby SNR to add to the background. The parameters (see below) of the considered accelerator of e^- and p are mainly due to the break at ~ 1 TeV in the all-lepton flux. Particles are confined inside the SN shock as long as their energy is lower than an *escape energy* $E_{\rm esc}$. This implies an energy-dependent release time that is regulated by the different stages of the SNR evolution and is different for protons and electrons. A parametrization of the escape time is described in F21b, where parameters are chosen based on dedicated observations. After escaping, particles are injected into the ISM according to the luminosity function $L(t) = L_0 \Big/ \left(1 + \frac{t}{\tau_{\rm d}}\right)^{\alpha_{\rm d}}$. In this work, the best fit is obtained for $\tau_{\rm d} = 10^5$ yr, $\alpha_{\rm d} = 2$.

3.1 Results: All-lepton spectrum

In Figure 1 (left) we show the $e^+ + e^-$ propagated spectrum plotted against data from AMS-02 [17], CALET [9] and H.E.S.S. [8]. The smooth background (red dashed line) is the sum of: (i) primary e^-, injected with DRAGON with a power-law spectrum $\Gamma_{\rm inj}^{\texttt{DRA}\,e^-} = 2.74$ and a cutoff $E_{\rm cut}^{\texttt{DRA}\,e^-} = 20$ TeV that is estimated equating the acceleration and loss timescales [18]; (ii) secondary $e^\pm$, fixed by the DRAGON-propagated primary species; (iii) a smooth *extra component* of primary $e^+ + e^-$ pairs, that represents the convolution of a large ($\mathcal{O}(10^4)$) number of old ($t_{\rm age} > 10^6$ yr) pulsars (see [11]). The secondaries and the *extra component* contribute to the background at the percent level. The blue dashed curve represents the total contribution from the class of sources generating lepton pairs (here we invoke pulsars). The three solid curves correspond to the contribution from the hidden remnant discussed in this work, computed by solving Equation (1) for different ages. The electron population is injected with a single power-law (slope $\Gamma_{\rm inj}^{e^-} = 2.45$). The difference with

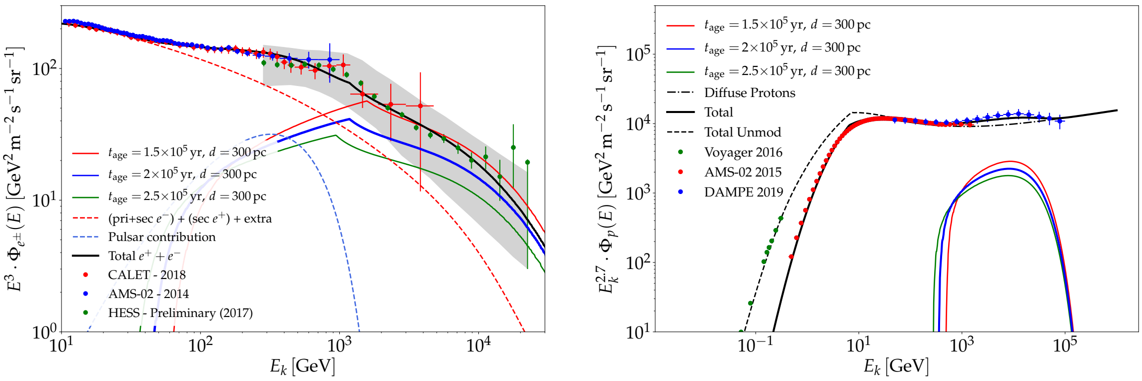

Figure 1: Left: the all-lepton spectrum as the sum of a smooth background of primary e^- + secondary $e^\pm$ + extra $e^\pm$ (red dashed line), a fit to the e^+ (blue dashed line) and the single-source contribution calculated in this work for $t_{\rm age}$ (blue solid line). Right: the proton spectrum, resulting from the sum of `DRAGON` modulated spectrum (black solid) and the solution of the single-source transport equation for $t_{\rm age}$ (blue solid line). Our reference age is $t_{\rm age} = 2 \cdot 10^5$ yr, while others (red and green solid lines) are added for comparison.

respect to the proton injection slope (see next section) is well justified by synchrotron losses that electrons undergo before being released [19]. The total energy budget associated to the leptonic population is $\simeq 4.5 \cdot 10^{47}$ erg, that, injected by a SNR with typical energy $E_{\rm SNR} = 10^{51}$ erg, corresponds to an efficiency of conversion into leptons of $\sim 10^{-4}$. Finally, the black curve is the sum of all the contributions, where we have chosen the source of age $t_{\rm age} = 2 \cdot 10^5$ yr as reference (blue solid). For what concerns $L(t)$, we vary $\alpha_{\rm d} \in [1, 3]$ and report negligible variations in the spectrum. On the other hand, while varying $\tau_{\rm d}$ in the range $[10^4, 2 \cdot 10^5]$ yr does not qualitatively change the results, smaller values cannot reproduce the data above the $\sim$ TeV break. Looking at $L(t)$, this shows that a burst-like injection from the source is disfavored by the high-energy data.

3.2 Results: Proton spectrum

The proton data are characterized by a hardening at $\sim$ 200 GeV and a softening at $\sim$ 13 TeV. Here, we connect this feature to the same hidden remnant considered in the previous section.

In Figure 1 (right), we show our result for different ages of the nearby remnant (green, red and blue solid lines). They are calculated assuming a power-law injection spectrum of $\Gamma^p_{\rm inj} = 2.1$, and an exponential high-energy cutoff at $E_{\rm cut} = 20$ TeV, chosen to match the *bump* observed by DAMPE, compatible with a maximum escape energy of $\sim$ PeV at earlier stages ($\lesssim 10^3$ yr) of the SNR. The normalization is consistent with a hadronic energy budget $\simeq 2.5 \cdot 10^{49}$ erg, which corresponds to an efficiency of $\sim$ 10% in accelerated protons. Data points are from AMS-02 [2], Voyager [20] and DAMPE [5]. The smooth background is calculated using `DRAGON` [11] with the proton slope $\Gamma^{{\rm DRA}\, p}_{\rm inj} \simeq 2.4$. The three solid lines are solutions of Equation (1) in the limit of negligible losses ($b(E_{\rm t}) \approx b(E) \to 0$), for different ages. The sum of the contributions is considered for the source of age $t_{\rm age} = 2 \cdot 10^5$ yr. The total modulated (unmodulated) flux associated to this case is shown as a black solid (dashed) line, with an effective potential $\langle \phi_{\rm mod} \rangle = 0.54$ [21].

3.3 CR dipole anisotropy

The CR dipole anisotropy (DA) provides a crucial complimentary probe of the model proposed. Indeed, the detected high degree of isotropy (up to $\sim 10^{-3}$) is especially constraining for the contribution from a local source. In this section we compute the DA associated with the hidden remnant, as described in F21b. The interpretation of a single source as the origin of the spectral feature in the proton spectrum between 1 TeV and 10 TeV is heavily challenged in the context of a diffusion setup characterized by a single power-law. This consideration led recent works to consider more complex (although not fully justified) diffusion scenarios. Here, we consider instead the transport scenario described above, suggested by the hadronic hardening reported by AMS-02.

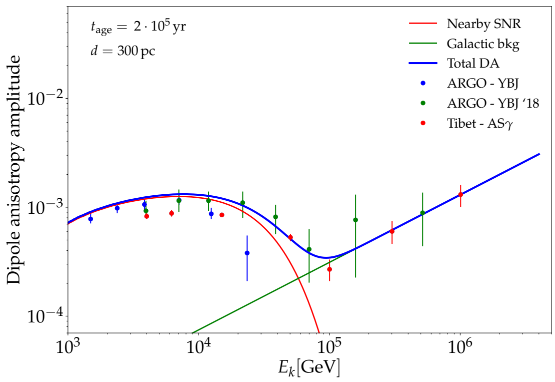

Figure 2: Cosmic-ray DA amplitude, as the sum of the background anisotropy (green solid line) and the single-source contribution (red solid line) for the age $t_{\rm age} = 2 \cdot 10^5$ yr.

In Figure 2, we show that the paradigm described in this work is compatible with the current anisotropy data. The DA is computed as the sum of two components: (i) the single-source contribution, that assumes directional observations; (ii) the averaged anisotropy of the large-scale background. The second component typically points towards the Galactic center and can be assumed to be a simple power-law [22]. We calculated this contribution using the fit parameters found in [6], $(c_1, c_2) = (1.32 \cdot 10^{-3}, 0.62)$, where the fit function is $\Delta_{\rm bkg} = c_1 \left(\frac{E}{1\,{\rm PeV}}\right)^{c_2}$. The result is the green solid line in the figure. On the other hand, the single-source contribution corresponds to the red solid line, for the source of age $t_{\rm age} = 2 \cdot 10^5$ yr. The plotted points are from ARGO and Tibet-ASγ (see [22] and references therein.)

We stress that the DA here computed was obtained without any fine tuning of the parameters. It was indeed the result of our novel approach to implement the $D(E)$ for the single-source particles, which, according to Equation (2), has a hard slope at high energies ($\delta \lesssim 0.2$ at $E > 10$ TeV).

4. Conclusions

In this paper we proposed the idea that the spectral feature at ~ 13 TeV in the proton spectrum reported by DAMPE, together with the spectral break at ~ 1 TeV measured by H.E.S.S. in the lepton spectrum, have a common origin and can be associated to a nearby, fading SNR. This simultaneous interpretation is of paramount importance, since SNRs accelerate both electrons and protons.

We computed the propagation of cosmic particles from such object in a spherically symmetric setup and assuming a luminosity that declines over time, and found that the most relevant observables can be simultaneously reproduced. The key ingredient in the calculation is a transport setup based on a diffusion coefficient characterized by a smooth transition to a progressively harder rigidity-scaling at higher energies, as suggested by the light nuclei spectra measured by the AMS-02 Collaboration. This feature allowed us to reproduce the cosmic-ray anisotropy data without any further assumptions. Moreover, the combined leptonic and hadronic data led us to characterize the properties of the particles accelerated by such object in good agreement with theoretical expectations.

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