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The Local Bubble as a cosmic-ray isotropizer

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Abstract. The arrival directions of energetic positrons and electrons convey fundamental information on their origin. PAMELA, and more recently AMS, have measured an anomalous population of energetic positrons, which cannot be explained in standard cosmic ray propagation models. Two possible sources have been extensively discussed: astrophysical point sources, such as local pulsars, and dark matter. In the first case an anisotropy in the flux of energetic particles is expected. Reliable predictions of the level of anisotropy need to account for the Sun's peculiar environment: the Sun resides in the so-called Local Bubble, an underdense region, embedded in a dense wall of molecular clouds. This structure is expected to act as an efficient cosmic-ray isotropizer. Using realistic assumptions on the impact of the Local Bubble on cosmic-ray diffusion, we demonstrate that the Local Bubble can indeed dilute the directional information of energetic positrons and electrons.

1 Introduction

We examine the impact of local structures on the cosmic-ray (CR) electron and positron spectra and anisotropies in CR arrival directions. Electrons and positrons suffer severe energy losses due to synchrotron emission and Inverse Compton scattering on the Interstellar Radiation Field: their propagation length decreases significantly with increasing energy from values of around 10 kpc at GeV energies to 600–900 pc at 1 TeV. With propagation distances as low as a few hundred parsecs, structures in the local interstellar medium (ISM) may have a sizeable effect on local spectra and arrival directions. This is different for hadrons, where the propagation length is comparable to the diameter of the gaseous disk for energies above 10 GeV.

The most prominent structure in our local interstellar medium is the so-called Local Bubble (LB), a particular underdense void containing our Solar system close to its center, surrounded by a wall of dense molecular clouds. The shape of the region is similar to a chimney, with radii between 50 and 150 pc (Abt, 2012); the asymmetric shape, elongated perpendicularly to the Galactic plane and opened towards the halo, is shown in several papers (see e.g. Welsh et al., 1999). The Local Bubble is connected via low-density "tunnels" to other similar nearby structures (see e.g. Plucinsky, 2009). These huge connected cavities filled with hot ionized gas are expected to originate from supernova explosions (Maíz-Apellániz, 2001) and should be present in every region of the Galaxy, making the Galactic plane a very inhomogeneous structure of underdense regions surrounded by denser and colder magnetized molecular clouds, which are expected to confine CRs efficiently.

In the context of interpretations of the so-called positron excess (Adriani et al., 2013; Accardo et al., 2014), the local anisotropy in positron and electron fluxes is particularly important: a positive detection of a dipole anisotropy towards a known object (e.g. a pulsar) could prove the astrophysical origin of the positron excess. No detection of any anisotropy has been reported so far, but more and more stringent upper limits are being placed on the sum flux of electrons and positrons and on the separate positron flux. In this context, a structure like the Local Bubble can work as an efficient isotropizer of local CRs, even under general assumptions. A meaningful comparison between data and model prediction requires to properly take into account the complicated environment CRs have to cross on their way from the local sources to us.

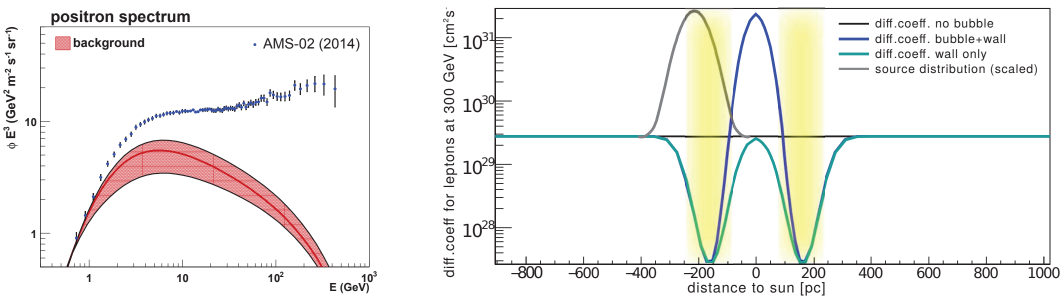

Figure 1. Left: predicted flux of secondary positrons for a set of about 13 000 models optimized to best decribe the flux of protons, antiprotons, the B/C ratio and the ^{10}Be/^{9}Be ratio (Kunz, 2014). The full red line indicates the best fit model to the above observables, the red band is the uncertainty given by the uncertainty on the transport parameters. Solar modulation was optimized for AMS-02 (Aguilar et al., 2014) for each model. Right: behavior of the diffusion coefficient in the Local Bubble for the two scenarios considered here. The gray line shows the pulsar source distribution.

2 Model

We use the DRAGON[1] code, which numerically solves the CR transport equation for all CR species, to simulate the propagation of $e^{\pm}$ accelerated by a nearby point source through the environment of the Local Bubble. The transport model was chosen to describe the locally measured proton and antiproton spectrum, the B/C ratio and the ^{10}Be/^{9}Be fraction. Using the given transport model, the contribution of secondary $e^{\pm}$ from proton-gas interactions in the ISM can be calculated. The predicted flux of secondary positrons is shown in Fig. 1. The solution is obtained separately for continuously distributed supernova remnants (where primary CR acceleration takes place for both, leptons and for hadrons; the latter also produce secondary positrons and electrons in subsequent interactions with the ISM), and for a pulsar point source (considered as electron-positron pair emitter). We model the source as a Gaussian with a width of 60 pc to account for the extension of the pulsar wind nebula; the source is assumed to be located at a distance $d = 200$ pc towards the Galactic center, just outside the bubble wall. The common electron and positron spectrum from pulsars is assumed to follow a power law with spectral index γ and an exponential cutoff at energy E_{cut}: $Q^{\mathrm{pulsar}}_{e^+,e^-} = q_0 (E/E_0)^{\gamma} \exp(-E/E_{\mathrm{cut}})$. The position and extension of the source with respect to the Local Bubble is illustrated by the gray line in Fig. 1. The source parameters are fixed to best describe the AMS-02 positron data.

To model the Local Bubble we implemented a region with increased spatial resolution surrounding the Sun in the DRAGON code. Within this region the normalization of the diffusion coefficient is allowed to vary as described in the following. In the most realistic model the bubble is a region of large diffusion coefficient surrounded by a thin, very confining region characterized instead by a low diffusion coefficient. The diffusion coefficient has the lowest value at a distance of 160 pc from the Sun. We discuss two scenarios: (a) a decrease of diffusion coefficient in the bubble wall by a factor of 100 with respect to the galactic value and an increase by a factor of 100 with respect to the galactic value at the Sun's position (dark blue line in Fig. 1). (b) a decrease of diffusion coefficient in the bubble wall by a factor of 100 with respect to the galactic value, while the diffusion coefficient at the position of the Sun is identical to the galactic value (sea green line in Fig. 1). More details on the technical implementation of the Local Bubble will be presented in a forthcoming publication.

[1] The code is public and available at: www.dragonproject.org (Gaggero et al., 2013).

3 Anisotropy and electron/positron spectra

For each scenario the injection spectrum of primary electrons from the continuous supernova remnant distribution is optimized to best describe the AMS-02 electron data. The pulsar injection spectrum index, cutoff energy and relative normalization of the pulsar contribution is optimized to the positron flux and positron fraction measured by AMS-02. The left side of Fig. 2 shows the impact of the Local Bubble scenarios on the electron and positron spectra. In the reference scenario (no Local Bubble, black line in Fig. 2) the data cannot be explained by a single pulsar. The plot shows how the Local Bubble, in both the implementations described here, has a sizable effect on the positron flux at low energy (we postpone a complete discussion to a more detailed work, given the huge uncertainties involved in this part of the spectrum on the modelling side). The corresponding anisotropies are numerically calculated for the position of the Sun according to $\delta = 3D(E)/c \cdot \nabla n_{\mathrm{e}}/n_{\mathrm{e}}$, where $D(E)$ is the local diffusion coefficient and n_{e} is the local electron density (Berezinskii et al., 1990). The spatial resolution of our model around the position of the Sun is 10 pc. The right side of Fig. 2 shows the anisotropy of the electron and positron sum flux. The standard scenario with no Local Bubble yields anisotropies at the level of 0.5 % in the entire energy range from 60 GeV to 1 TeV, which is comparable to the 95 % CL upper limits from

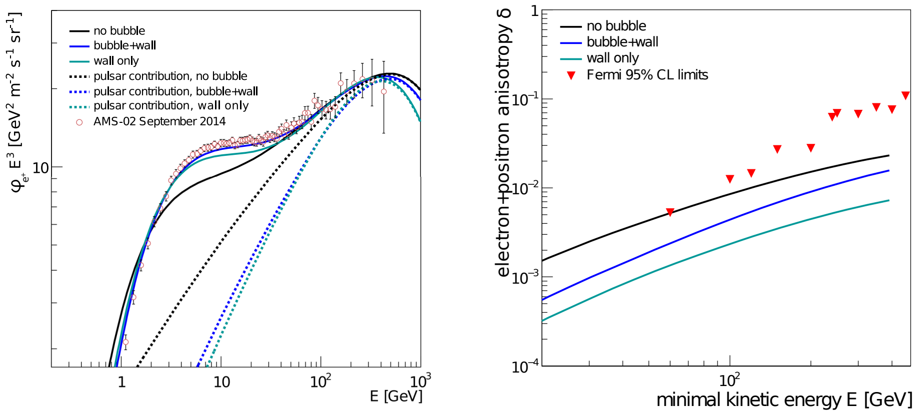

Figure 2. Left: local positron flux. The solar modulation is optimized for the data in each case. Data: AMS-02 (Aguilar et al., 2014). Right: electron + positron sum flux anisotropy. The x axis is in cumulative energies, with a maximum energy of 1 TeV. Data: Fermi-LAT (Ackermann et al., 2010).

Fermi. In the bubble + wall scenario the level of anisotropy is decreased by a factor of 2.3 in the entire energy range, while the wall only scenario yields a decrease by a factor of about 4.

4 Conclusion

We used general assumptions on the behavior of the diffusion coefficient in the Local Bubble to investigate the level of isotropization of electron and positron fluxes coming from a nearby point source (e.g. a pulsar). We tuned the source parameters so that the emission from the source provides a good fit of AMS e^+ and e^- spectra. We showed that the level of anisotropy expected from a local point source can be decreased by a factor of 4 by local changes in the diffusion coefficient, while the description of the local spectra of electrons and positrons is improved. We conclude that, under simple assumptions, the Local Bubble acts as an efficient CR isotropizer, with strong impact on the comparison between the prediction of the dipole anisotropy from local pulsars and the observed upper limit from Fermi-LAT.

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