Astroparticle Physics 85 (2016) 54–64

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

The nuclear window to the extragalactic universe

M. Erdmann*, G. Müller, M. Urban, M. Wirtz

Physics Institute 3A, RWTH Aachen University, D-52056 Aachen, Germany

ARTICLE INFO

Article history:
Received 6 July 2016
Revised 16 September 2016
Accepted 13 October 2016
Available online 14 October 2016

Keywords:
Astroparticle physics
Magnetic fields
Cosmic rays

ABSTRACT

We investigate two recent parameterizations of the galactic magnetic field with respect to their impact on cosmic nuclei traversing the field. We present a comprehensive study of the size of angular deflections, dispersion in the arrival probability distributions, multiplicity in the images of arrival on Earth, variance in field transparency, and influence of the turbulent field components. To remain restricted to ballistic deflections, a cosmic nucleus with energy E and charge Z should have a rigidity above $E/Z = 6$ EV. In view of the differences resulting from the two field parameterizations as a measure of current knowledge in the galactic field, this rigidity threshold may have to be increased. For a point source search with $E/Z \geq$ 60 EV, field uncertainties increase the required signal events for discovery moderately for sources in the northern and southern regions, but substantially for sources near the galactic disk.

1. Introduction

The origin of cosmic rays still remains an unanswered fundamental research question. Cosmic ray distributions of various aspects have been measured, most notably the steeply falling spectrum up to the ultra-high energy regime with cosmic ray energies even exceeding $E = 100$ EeV [1,2].

For ultra-high energy cosmic rays, deflections in magnetic fields should diminish with increasing energy, such that directional correlations should lead to a straight-forward identification of accelerating sites. However, even at the highest energies the arrival distributions of cosmic rays appear to be rather isotropic. Only hints for departures from isotropic distributions have been reported, e.g., a so-called hot spot [3], and a dipole signal [4]. At least with the apparent isotropy, limits on the density of extragalactic sources were derived which depend on the cosmic ray energy [5].

A recent determination of ultra-high energy cosmic ray composition from measurements of the shower depth in the atmosphere revealed contributions of heavy nuclei above ~5 EeV [6,7]. This observation may explain the seemingly isotropic arrival distribution as deflections of nuclei in magnetic fields scale with their nuclear charges Z.

Obviously, when searching for cosmic ray sources, a key role is therefore attributed to magnetic fields. The galactic field in particular is strong enough to displace original arrival directions of protons with energy $E = 60$ EeV by several degrees from their original arrival directions outside the galaxy [8]. The displacement angles for nuclei even reach tens of degrees [9]. The knowledge on the extragalactic magnetic fields is much less certain, but is likely to be less important than the galactic field [10] and is not studied in this contribution.

To identify sources of cosmic rays, rather precise corrections for the propagation within the galactic magnetic field are needed which in turn can be used to constrain the field [11]. Beyond this, effects of lensing caused by the galactic field have been studied which influence the visibility of sources and the number of images appearing from a single source [12]. The influence of turbulent contributions to the galactic field has also been studied in the context of lensing [13] and nuclear deflections [14].

In previous directional correlation analyses of measured cosmic rays, only the overall magnitude of deflections was taken into account, e.g. [15], or corrections for cosmic ray deflections were applied using analytic magnetic field expressions reflecting the spiral structure of our galaxy [16].

Recently, parameterizations of the galactic magnetic field have been developed which are based on numerous measurements of Faraday rotation [17,18], and in addition polarized synchrotron radiation for the second reference. Based on directional characteristics and the field strength of the parameterizations, deflections of cosmic rays are predicted to depend strongly on their arrival direction, charge and energy. In the following we will refer to the regular field with the bisymmetric disk model of the first reference as the PT11 field parameterization, and to the regular field of the latter as the JF12 field parameterization, respectively.

Angular distributions of cosmic rays in these galactic field parameterizations have been studied before, e.g., with respect to general properties of the JF12 parameterization [19], specific source

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* Corresponding author.
E-mail address: erdmann@physik.rwth-aachen.de (M. Erdmann).

http://dx.doi.org/10.1016/j.astropartphys.2016.10.002
0927-6505/

candidates [20], general properties of deflections and magnifications [21,22], and to the potential of revealing correlations between cosmic rays and their sources [23].

In this work we investigate whether cosmic ray deflections in the galactic magnetic field can be reliably corrected for, given the current knowledge of the field. To simplify discussions of energy and nuclear dependencies we will define rigidity as the ratio of the cosmic ray energy and number Z of elementary charges e

$$R = \frac{E}{Z\,e}\,. \tag{1}$$

In our investigations we use galactic coordinates as our reference system, with longitude l and latitude b. For a number of visualizations we use Cartesian coordinates alternatively with height z above the galactic plane, with the Earth being located at $(x_E, y_E, z_E) = (-8.5, 0, 0)$ kpc.

Based on the two field parameterizations PT11 and JF12 we initially discuss key distributions of cosmic ray deflection, dispersion effects in arrival distributions, directional variance in field transparency, and the influence of random field components. From the rigidity dependencies of these distributions, we recommend a minimum rigidity threshold above which cosmic ray deflection may be controlled in terms of probability distributions.

Furthermore, we take the different results of the two galactic field parameterizations as a measure of our current knowledge of the galactic field. We compare their cosmic ray angular deflections and study differences in the dispersion of arrival distributions. Finally, we study the practical consequences of galactic field corrections and their uncertainties by performing simulated point source searches and by quantifying the field impact in terms of discovery potential.

2. Field parameterizations

The two field parameterizations PT11 and JF12 each follow a different ansatz. Both take into account about 40,000 Faraday rotation measurements. The PT11 field has been fitted to two large sets of Faraday rotation measurements. The JF12 field has been adapted to several large sets of Faraday rotation measurements and to synchrotron polarization measurements, thereby increasing the information per analysed direction by two additional complementary measurements [21]. Both use the electron density model NE2001 [24] with an enlarged vertical scale for weighting the line-of-sight integrals of the magnetic field.

Fig. 1 shows the field strength as a function of the radial distance from the galactic center along the solar system line-of-sight and the distance perpendicular to the galactic plane. The fields exhibit different shapes and magnitudes; especially notable in Fig. 1a is the field extent of the JF12 parametrization above and below the galactic plane with non-negligible field strengths even at a distance of 10 kpc. The PT11 field (Fig. 1b), on the other hand, exhibits a rather concentrated halo field, which is centered around a distance of ~1.2 kpc to the galactic plane.

When studying the magnitude of angular deflections of cosmic rays resulting from these parameterizations, we take the angle β between the incoming direction to the galaxy and the arrival direction on Earth as a measure of the directional change (Fig. 2).

To get a first impression of the different deflections resulting from the two field parameterizations we use backward tracking techniques of antiprotons through the galactic field. With this technique we obtain individual trajectories for matter particles entering from outside the galaxy and then following the reverse path. The method ensures that every trajectory leads to observation on Earth.

In Fig. 3 we show the magnitudes of the angular deflections β of cosmic rays with rigidity $R = 60$ EV. The position in the map denotes the initial direction on Earth in galactic coordinates for the backtracked antiprotons. The color code refers to the magnitude of angular deflections which reach up to $\beta = 28^\circ$.

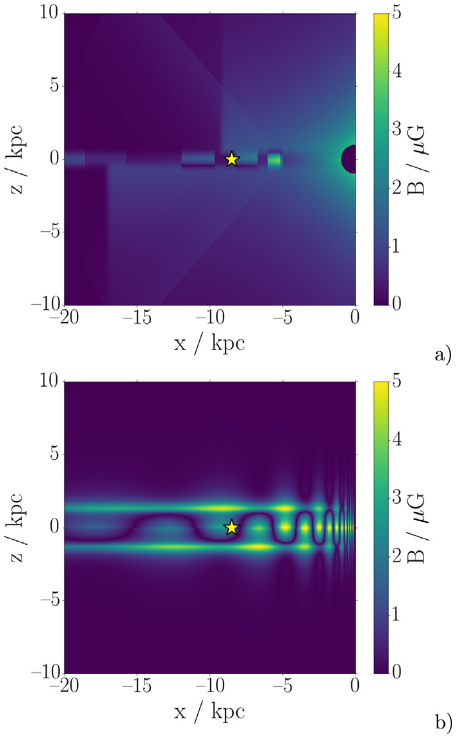

Fig. 1. Strength of the galactic magnetic field as a function of the distance from the galactic center along the solar system line-of-sight, and of the distance perpendicular to the galactic plane for a) JF12, b) PT11. The yellow star denotes our solar environment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

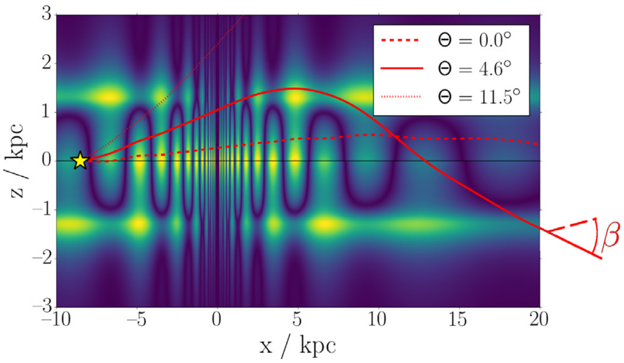

Fig. 2. Example trajectories of antiprotons originating on Earth with different initial angular directions Θ with respect to the galactic plane; directional change β between the direction on Earth and the direction outside the galaxy (PT11).

For the JF12 parameterization (Fig. 3a), deflections are largest near directions of the galactic center which is expected from the magnitude of the field shown in Fig. 1a. With the PT11 parameterization (Fig. 3b), deflections are largest in any direction near the galactic plane which is attributed to the strong disk field (Fig. 1b).

As expected, the differences in the field parameterizations relate directly to a different impact on cosmic ray deflections. In the following section we study a number of aspects related to the directional changes of cosmic rays when traversing the galactic field.

3. Impact of the galactic magnetic field on cosmic ray arrival

The goal of this section is to determine a kinematic regime where information on cosmic ray arrival directions can be obtained