C. R. Physique 15 (2014) 339–348

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Ultra-high-energy cosmic rays / Rayons cosmiques de ultra-haute énergie

The Galactic magnetic field and ultrahigh-energy cosmic ray deflections

Le champ magnétique galactique et la déflexion des rayons cosmiques ultra-énergétiques

Glennys R. Farrar

Center for Cosmology and Particle Physics, Department of Physics, New York University, USA

ARTICLE INFO

Keywords:
UHECR
Galactic magnetic field
Magnetic deflections

Mots-clés :
RCUHE
Champs magnétique galactique
Déflexions magnétiques

ABSTRACT

Our understanding of the Galactic magnetic field (GMF) has increased considerably in recent years, while at the same time remaining far from adequate. By way of illustration, the Jansson and Farrar (2012) (JF12) GMF model is described, emphasizing how it is constrained and which features are robust or likely to change, as modeling and constraining data improve. The most urgent requirements for the next phase of modeling are a more realistic model for the relativistic electron distribution (in order to reduce the systematic error associated with interpreting synchrotron data) and a better theoretical understanding of the origin of the large-scale coherent field (in order to develop a better phenomenological parameterization of the field). Even in its current stage of development, the JF12 model allows some important conclusions about UHECR deflections in the GMF to be formulated.

RÉSUMÉ

Notre compréhension du champ magnétique galactique (GMF) s'est considérablement améliorée au cours des dernières années, mais reste largement insuffisante. À titre d'illustration, le modèle GMF de Jansson et Farrar (2012) (JF12) est décrit ici, en insistant sur la manière dont il est contraint et sur ses caractéristiques, qu'elles soient robustes ou, au contraire, susceptibles de changer avec l'amélioration de la modélisation et des données. Les besoins les plus urgents pour la prochaine phase de modélisation sont, d'une part, un modèle plus réaliste de la distribution des électrons relativistes (ce qui permettra de réduire les incertitudes systématiques associées à l'interprétation des données d'émissions synchrotron) et, d'autre part, une meilleure compréhension théorique de l'origine du champ galactique cohérent sur les grandes échelles (afin de développer une meilleure paramétrisation phénoménologique du champs). Le modèle JF12, même dans sa version actuelle, permet de formuler quelques conclusions importantes sur la déflexion des RCUHE dans la Galaxie.

E-mail address: gf25@nyu.edu.

http://dx.doi.org/10.1016/j.crhy.2014.04.002

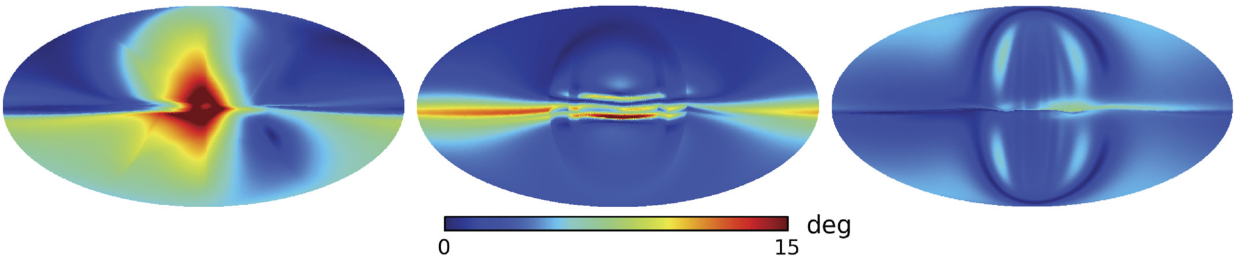

Fig. 1. The magnitude of the deflection of a 60 EeV proton, displayed by arrival direction, in (left to right) the JF12, SR10 and PTK11 models of the large-scale GMF.

1. Introduction

Our understanding of magnetic fields in the Milky Way and of the global structure of the GMF has developed over many decades. A recent review of the magnetic fields in galaxies with a discussion of observations is that of Beck and Wielebinski (2013) [1]; a classic review of the previous generation of GMF models and their observational constraints, and application of dynamo theory to interpret the observations is Beck, Brandenburg, Moss, Shukurov and Sokoloff (1996) [2]. It has only been in the past few years that the present generation of more sophisticated and quantitatively-constrained models of the GMF have emerged.

Even with these improved models, predicting UHECR deflections remains uncertain, as seen from Fig. 1 which shows the magnitudes of UHECR deflections predicted by three recent GMF models due to Sun and Reich (SR10, based on [3] incorporating the parameter update of [4]), Pshirkov, Tinyakov and Kronberg (PTK11, [5]) and Jansson and Farrar (JF12, [6]). Evidently, determining the astrophysical source(s) of UHECRs via their correlations with candidate source catalogs is fraught with uncertainty, even if the charge and energy of each UHECR were perfectly known, until we know the GMF with greater confidence. Nonetheless some general expectations for UHECR deflections are emerging, as discussed below.

Trustworthy 3D models of the GMF are also needed to calculate the propagation of Galactic cosmic rays and predict Galactic diffuse gamma emission, with wide-ranging implications including interpreting possible signatures of Dark Matter annihilation in the Galaxy. Another important application is modeling the spatial dependence of the synchrotron emission spectral index, needed for accurate foreground subtraction to obtain the cosmological CMB signal.

2. Observables to constrain the GMF

Faraday Rotation Measures (RMs) of extragalactic sources have always been primary constraining data for Galactic magnetic fields. Rotation measures depend on the line-of-sight field; in units of rad m^{-2},

$$\mathrm{RM} = 0.81 \int_0^L \left(\frac{n_\mathrm{e}(l)}{\mathrm{cm}^{-3}}\right)\left(\frac{B_\parallel(l)}{\mu\mathrm{G}}\right)\left(\frac{\mathrm{d}l}{\mathrm{pc}}\right) \tag{1}$$

where L is the distance to the source and n_e is the density of ionized electrons, which is dominated by the *thermal* electron density. The sheer number of extragalactic sources providing all-sky, well-measured RMs is roughly 2 orders of magnitude larger than in the early 1990s, and will increase by another 1 or 2 orders of magnitude within the decade.

Each extragalactic source (primarily distant quasars) has an intrinsic RM due to magnetic fields in the AGN and its host galaxy, which can be large compared to the Galactic contribution. However the extragalactic contributions are uncorrelated from one source to another, so their impact is to produce an approximately isotropic variance beyond that due to random fields in the Galaxy. Increasing the number of extragalactic sources in the RM dataset benefits the GMF constraints by reducing the fluctuations in the mean RM of each analysis pixel.

Complementing RM, we now have all-sky maps of polarized and unpolarized Galactic synchrotron emission from WMAP and soon also from Planck, as well as targeted observations of Galactic structures and high-resolution synchrotron mapping of external galaxies such as in the CHANG-ES survey [7]. Galactic synchrotron emission provides a constraint on the GMF which is complementary to that from RMs, because synchrotron emission depends on the transverse magnetic field, weighted by the relativistic (also called cosmic ray) electron density, n_cre. The polarization state of linearly polarized light is specified by the Stokes parameters Q and U, with each proportional to the polarized intensity (PI) and the relation between Q and U encoding the orientation of the transverse component of the coherent magnetic field (cf., [8]), with

$$\mathrm{PI} \sim \int_0^L n_\mathrm{cre}(l) B_\perp^2(l)\,\mathrm{d}l \tag{2}$$

Exploiting the relationships in Eqs. (1) and (2) between the magnetic field and the physical observables depends on knowing the thermal and relativistic electron distributions. The standard model for n_e is the Cordes–Lazio NE2001 model [9],