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Review

Origin of small-scale anisotropies in Galactic cosmic rays

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ABSTRACT

The arrival directions of Galactic cosmic rays are highly isotropic. This is expected from the presence of turbulent magnetic fields in our Galactic environment that repeatedly scatter charged cosmic rays during propagation. However, various cosmic ray observatories have identified weak anisotropies of various angular sizes and with relative intensities of up to a level of 1 part in 1000. Whereas large-scale anisotropies are generally predicted by standard diffusion models, the appearance of small-scale anisotropies down to an angular size of 10° is surprising. In this review, we summarize the current experimental situation for both the large-scale and small-scale anisotropies. We address some of the issues in comparing different experimental results and remaining questions in interpreting the observed large-scale anisotropies. We then review the standard diffusive picture and its difficulty in producing the small-scale anisotropies. Having set the stage, we review the various ideas and models put forward for explaining the small-scale anisotropies.

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1. Introduction

The Earth's atmosphere is constantly bombarded by a flux of charged particles, called cosmic rays. There is a consensus that at energies between a few hundreds of MeV and a few PeV (10^{15} eV), cosmic rays are of Galactic origin and most likely connected to the deaths of massive stars [1,2]: supernova remnants (SNRs), pulsars, or pulsar wind nebulae. These Galactic sources are mostly distributed in the Galactic disk. Therefore, if cosmic rays were propagating rectilinearly, these sources would be visible in the distribution of arrival directions, very much like the sources of electromagnetic radiation. However, the observed distribution of cosmic ray arrival directions is highly isotropic, to better than 1 part in 1000 or even 10,000 depending on energy. This implies a mechanism that efficiently randomizes the arrival directions over Galactic distance scales.

In the presence of a turbulent magnetic field, a cosmic ray nucleus with charge Z can scatter resonantly with turbulence modes with a wavelength of the order of the gyroradius $r_g \simeq 1.1(\mathcal{R}/\mathrm{PV})/(B/\mu\mathrm{G})$ pc (1 pc $\simeq 3 \times 10^{18}$ cm) [3–6], where $\mathcal{R} \equiv pc/(Ze)$ is the cosmic ray's rigidity. (In a static magnetic field, the trajectory of a cosmic ray depends only on this ratio of its momentum p and charge Z.) Cosmic rays are thus performing a random walk and are losing any correlation with their initial directions over a few scattering times. After long time scales this results in a diffusion process and it is this diffusion that quickly erases the information on the distribution of sources. Since cosmic rays with larger rigidity can escape the Galactic environment more quickly, the local cosmic ray spectrum is softer than the initial cosmic ray emission spectrum from diffusive shock acceleration [7–11]. Specifically, shock acceleration predicts in its simplest incarnation an $\mathcal{R}^{-2}$ spectrum, but can also explain a considerably softer spectrum [12–14], e.g. $\propto \mathcal{R}^{-2.4}$. Escape then softens this spectrum by a factor $\mathcal{R}^{0.3}$ (for a Kolmogorov spectrum of magnetic turbulence in the interstellar medium), thus producing a propagated spectrum $\propto \mathcal{R}^{-2.7}$ as observed for Galactic cosmic rays below a few PeV.

At even higher energies, particle identification is more difficult (as observations rely on cosmic ray induced air showers), and traditionally only the all particle spectrum (as a function of cosmic ray energy E) could be determined, shown in Fig. 1. At energies above a few PeV (a feature called the cosmic ray "knee"), the observed all particle spectrum, shown in Fig. 1, steepens to $\propto E^{-3}$ before further steepening to $\propto E^{-3.3}$ at a few hundred PeV (the second "knee"). Just below 10^{19} eV the spectrum hardens again (the "ankle") before cutting off around 5×10^{19} eV. Where exactly the transition from Galactic to extra-galactic sources is taking place is very much an open question, and different models interpret the spectral features differently.

Another hint for diffusion being the most important mechanism of cosmic ray transport comes from the observation of so-called cosmic ray secondary species (e.g. Lithium, Beryllium, Boron, sub-Iron elements). The relative contribution of these cosmic rays is larger than the observed solar abundance, which is believed to be representative for the abundances at cosmic ray sources. Consequently, all the observed cosmic ray secondaries must be produced during the propagation of cosmic ray primaries (e.g. protons, Helium, Nitrogen, Oxygen, Carbon, Iron) by spallation on interstellar gas. The integrated matter density, that needs to be traversed in the interstellar medium (91% p, 9% Helium by number [16]) to produce the secondary fluxes, is inferred to be of the order of a few g cm^{-2}. With the typical distance scale for Galactic sources of the order of a few kiloparsec and a number density of $n_{\mathrm{gas}} \simeq 1$ cm^{-3} in the Galactic disk, the column density for rectilinear propagation is falling three orders of magnitude short. This requires that the observed flux of cosmic rays must have traversed the Galactic disk many times after emission, which is also implied by diffusion.

However, it can easily be seen that diffusion does not imply that the arrival directions of cosmic rays are completely isotropic. For instance, the relative motion of the observer with respect to a frame in which the cosmic ray distribution was completely isotropic would induce a weak dipole anisotropy in the direction of the motion, the Compton–Getting effect [17,18]. Moreover, an asymmetric distribution of sources introduces a local density gradient which implies, by Fick's law, the presence of a net flux. In the case of isotropic diffusion, this will be visible in' the cosmic ray arrival direction as a dipole anisotropy pointing into the upstream direction. This has been advertised [19–23] as a means of finding the direction of the bulk of sources or even young nearby sources which can be dominating the local cosmic ray gradient. However, none of these predictions have so far been unambiguously identified in the cosmic ray data. In particular, simple models of isotropic cosmic ray diffusion predict dipole anisotropies of TeV–PeV cosmic rays that are much larger than the observed values [24–31]. This discrepancy has been dubbed the cosmic ray "anisotropy problem" [24].

Together with the overall cosmic ray spectrum and the relative abundances of different species, anisotropies constitute one of the classical observables of cosmic ray physics. First hints of a large-scale anisotropy were already observed in the early 1930s, but the systematic and statistical uncertainties of these observations were quite large [32]. A systematic study of the small effect became possible in the 1950s due to data collected by large underground muon detectors and extended air shower arrays, see [33]. We refer to the comprehensive review by Di Sciascio & Iuppa [33] for the history of cosmic ray anisotropy studies. Only rather recently, however, have experiments achieved the necessary level of statistics to be able to find anisotropies of the order of 10^{-3} or even 10^{-4} [34–43]. To the surprise of many, besides the expected large-scale anisotropy mentioned above, there is structure in the maps of arrival directions on much smaller scales, at least down to 10°.