Anisotropy of cosmic rays at 10^{18} eV from single Galactic sources

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Abstract

We investigate the possibility that point sources of 10^{18} eV protons exist in the Galaxy and we calculate their images on the sky. They depend strongly on the adopted model of $B_{\rm reg}$ and a value of $B_{\rm irr}$, and on particle energy. It seems that for any model there is always a narrow energy region for which the delayed particles form a quite compact image, significantly shifted away from the direction towards the source.

1. Introduction

Recent analysis of the AGASA data shows an anisotropy in arrival directions of cosmic rays with energies $10^{17.9} - 10^{18.3}$ eV, with an excess from the direction near the Galactic Centre [5,3] and the Cygnus region [5]. In our previous paper [2] we have considered the propagation of charged particles from sources located in the Galactic Centre, applying two models of the Galactic magnetic field in the disk and halo. We have shown that delayed particles may arrive in bulks (in time and directions) mimicking existence of point sources in directions quite different than that towards their source. Here we consider sources located at other interesting regions of the Galaxy in order to check whether our previous conclusions could be applied to other source positions as well.

2. Images of point proton sources

Protons ejected from a point-like source propagate in the Galactic magnetic field, consisting of regular $B_{\rm reg}$ and irregular $B_{\rm irr}$ components. We adopt two different models for $B_{\rm reg}$: model I - based on the observations of other spiral galaxies (Urbanik et al. [6]); model II - the bisymmetric field model with field reversals and odd parity (BSS-A) proposed by Han & Qiao [4]. We calculate numerically proton trajectories with energies corresponding to those of the AGASA excess ($10^{17.9} - 10^{18.3}$ eV) from different locations in the Galaxy. For 1.2×10^6 protons ejected isotropically from a point source we record the directions of particles intersecting a sphere of radius 250 pc centred at the Earth. These events

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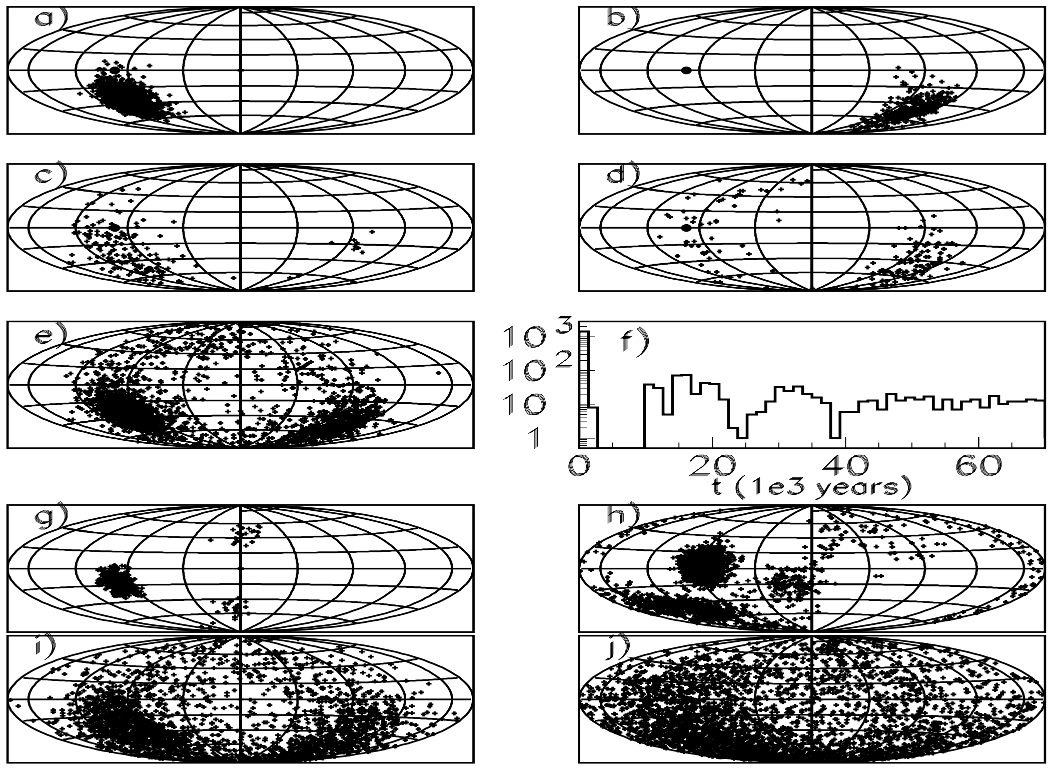

Fig. 1. Arrival directions of protons injected from a source 2 kpc away towards the Cyg OB2 association (marked by the big dot) for $B_{\rm reg}$ from [6] and $< B_{\rm irr} > 2\mu$G in the disk and 0.5μG in the halo. a) to d): directions of particles with $E = 10^{18}$ eV arriving in consecutive time delay intervals: a) $(0-5)\times 10^3$ yrs, b) $(1-2.5)\times 10^4$ yrs, c) $(2.5-4)\times 10^4$ yrs, d) $(4-6)\times 10^4$ yrs. e) Arrival directions integrated over time. f) Time delay distribution. g) As in e) but for 2×10^{18} eV. h) As in e) but for $B_{\rm reg}$ [4]. i) and j) As in e) but for $< B_{\rm irr} >$ 2 and 4 times stronger.

are treated as observed by a detector on the Earth.

Figs. 1a-d show the arrival directions of protons injected by a point source located at the distance of 2 kpc in the direction of the Cygnus region. This distance corresponds to the location of the Cyg OB2 association coinciding with the unidentified HEGRA TeV γ-ray source [1]. The images of such a source appear at different places on the sky depending on time after injection. Their locations depend also strongly on the proton energy (Figs.1e and 1g). The images are quite extended with the radius about $20^{\rm o} - 30^{\rm o}$. Moreover, the distribution of the images on the sky strongly depends on the applied model of $B_{\rm reg}$ (see Figs.1e and 1h). The influence of the irregular component of the galactic magnetic field on the sharpness of the images is seen by comparing Figs.1i,j with Fig.1e.

The dependence of the images on the distance to the Earth, for different $B_{\rm reg}$ is investigated in Fig.2, by considering a source of protons located 11 kpc away, i.e. at the position of Cyg X-3. The number of arriving particles is now

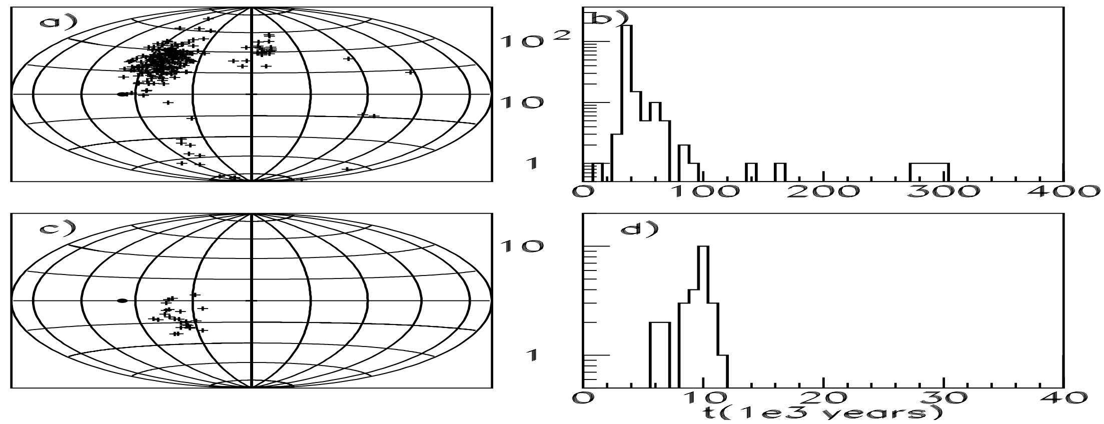

Fig. 2. Arrival directions of protons $E = 2 \times 10^{18}$ eV (integrated over time). Source 11 kpc away towards the Cyg X-3 (marked by the big dot) in a) $B_{\rm reg}$ from [4] and b) $B_{\rm reg}$ from [6]. $< B_{\rm irr} >= 2\mu$G in the disk and 0.5μG in the halo. The corresponding time delay distributions are shown on the right.

much lower than that from the source at 2 kpc. The broad images of the source (extending $\sim 10^{\rm o} - 15^{\rm o}$) are shifted by $\sim 30 - 40^{\rm o}$ away from the direction of the source. Their location and the arrival time of the bulk of particles depend on the applied model of $B_{\rm reg}$.

The dependence of the images on the location inside the Galaxy is investigated in Fig.3a in which the image of a point source of protons with energies 10^{18} eV, located 2 kpc away towards the Galactic antycentre (the Crab Nebula), is shown. The image consists of an excess of particles centered on the direction from the source (propagated almost along straight lines) and a circle of particles arriving regularly at later times with the characteristic time delay of $\sim 2.5 \times 10^4$ yrs (see the second peak in the time distribution). These particles circle in the magnetic field which is quite regular on the distance scale of ~ 1 kpc in the antycentre direction. The image is completely different from that caused by particles injected at the same distance of 2 kpc but located towards the Cygnus region (see Figs.1e and 2a). Figs.3b and 3c illustrate a spreading out of the images and arrival times of particles with increasing $B_{\rm irr}$. If $B_{\rm irr}$ was a few times stronger than $B_{\rm reg}$ then, even for a source 2 kpc away, the distribution of particle arrival directions would be close to isotropy.

3. Conclusions

By comparing our calculated proton anisotropies for the two magnetic field models we conclude that the propagation of charged particles is very sensitive to the structure and strength of it, as well as to the particle energies . The two models, both based on experimental observations, give totally different predictions concerning the particle angular distribution on the sky. However, for any

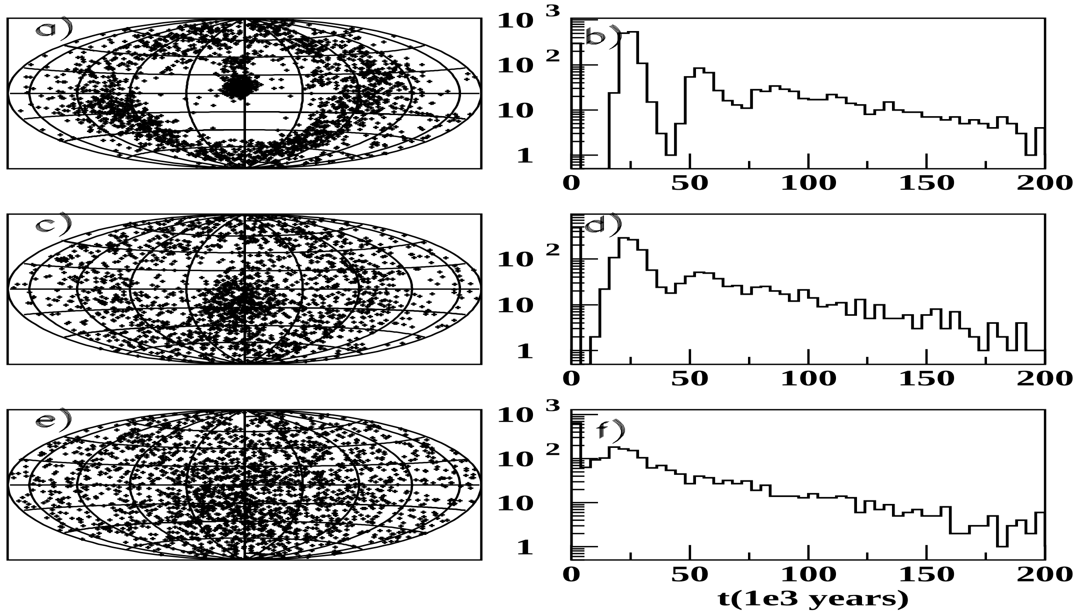

Fig. 3. As in figure 2 but for protons with $E = 10^{18}$ eV injected by a point source 2 kpc away towards the antycentre (in the centre of the map) for $B_{\rm reg}$ from [6] and different $< B_{\rm irr} >$: a) 2μG in the disk and 0.5μG in the halo, b) two times stronger, c) four times stronger.

field model with a large scale regular field in the halo there is a narrow energy region (a factor of 2 or so) such that charged particles form quite compact images at significant angular distances from their actual direction. At a lower energy, particle arrival directions become isotropic, at a higher one - particles propagate along straigth lines, indicating towards the source.

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4. References

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