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Propagation of extremely high energy cosmic rays from sources within the Galaxy

W. Bednarek, M. Giller, and M. Zielińska

Department of Experimental Physics, University of Łódź, ul. Pomorska 149/153, 90-236 Łódź, Poland

Abstract. Recent analyses of the anisotropy of cosmic ray arrival direction around 10^{18} eV show significant excesses from the regions close to the Galactic Center and Cygnus. Our aim is to check whether such anisotropies can be caused by single sources. We investigate propagation of protons in the Galactic regular and turbulent magnetic fields assuming that these particles are injected by short lived discrete sources within our Galaxy. We show that the effect of the regular magnetic field may cause a double image of the source, with quite large angular distances from the actual direction. The image is strongly dependent on time elapsed from particle ejection and is also very sensitive to their energy.

1 Introduction

Recent analysis of the AGASA data shows anisotropy in arrival directions of cosmic rays with energies $10^{17.9} - 10^{18.3}$ eV with excesses from the direction near the Galactic Center (4.5σ) and Cygnus region (3.9σ) (Hayashida et al. 1999). The existence of a point like excesss at $\sim 7.5^{\rm o}$ from the Galactic Center (GC) has been confirmed by the analysis of the SUGAR data (Bellido et al. 2001). However no excess from GC itself is seen, which would suggest that this region may not be the source of these particles. Bellido et al. propose that such point like excess might be caused by relativistic neutrons which are able to reach the Earth from the distances as large as that to GC. Relativistic protons, likely responsible for neutron injection, escape from the source and may reach the Earth after propagation in regular and turbulent galactic magnetic fields. The propagation of protons with energies $\sim 10^{18}$ eV from the Galactic Center has been recently examined in the context of above mentioned results by Clay et al. (2000). It was found that it is difficult to explain the observed location of the excess by deflection of protons in the Galactic magnetic fields (Clay et al. 2000, Bellido et al. 2001). However, with increasing energy the role of the Galactic field increases in comparison with that of the irregular one and particle propagation starts to depend strongly on energy (Giller et al. 1994). We have decided to check its dependence in more detail.

Correspondence to: M. Giller (mgiller@kfd2.fic.uni.lodz.pl)

2 Sources of EHE particles within the Galaxy

We investigate propagation of protons in the Galactic magnetic fields from the location of the source consistent with the observed AGASA and SUGAR excess close to the Galactic Center, assuming that particles with different energies are injected by the short lived source, e.g. a very young pulsar (e.g. Blasi et al. 2000; Bednarek & Protheroe 2001; Giller & Lipski 2001). We follow the suggestion that pulsars winds are able to accelerate particles to energies corresponding to the full potential drop available across the polar cap region. In order to accelerate protons $> 10^{18}$ eV the pulsar has to be born with parameters which fulfil the condition $P_{\rm ms} \leq 2.6 B_{12}^{1/2}$. If the pulsar loses its rotational energy only on electromagnetic waves, then its period changes according to the formula $P_{\rm ms}^2(t) = 1.04 \times 10^{-9} t B_{12}^2 + P_{0,ms}^2$. It stops accelerating protons above 10^{18} eV at the age $t_{\rm acc} \approx 1.25 \times 10^{10} B_{12}^{-1}$ s. Therefore the period during which protons can be accelerated above 10^{18} eV is relatively short, and we can consider such injection as instantaneous.

3 Propagation of EHE protons

Protons injected from the point-like source propagate in the Galactic magnetic field which has the regular $B_{\rm reg}$ and irregular $B_{\rm irr}$ components. For $B_{\rm reg}$ we apply the model proposed by Urbanik et al. (1997), which consists of a toroidal component, confined mainly to the disk, and a large scale poloidal component. The irregular field $B_{\rm irr}$ is a sum of many plane waves with isotropically distributed wave vectors and amplitudes described by the Kolmogorov power spectrum. Its mean value is 2 μGs in the disk with $z \pm 500$ pc, and 0.5 μGs in the spherical halo with radius 20 kpc.

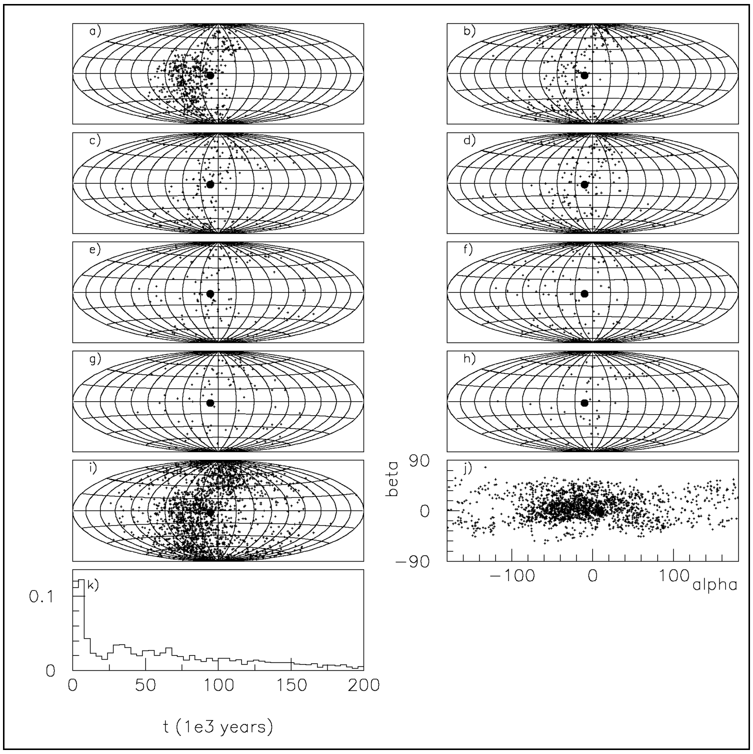

Fig. 1. Arrival directions of protons with energies 10^{18} eV injected by a point source at a distance of 8.4 kpc towards the direction of the AGASA excess (marked by the large dot). Maps (in galactic coordinates) from a) to h) show directions of particles arriving with consecutive time delay intervals of 2×10^4 yr, i.e. a) is for $0 - 2 \times 10^4$ yr, b) $2 \times 10^4 - 4 \times 10^4$ yr, ... , h) $1.4 \times 10^5 - 1.6 \times 10^5$ yr. i) Arrival directions for all times, j) Ejection directions of particles arriving to the Earth. The large dot shows the direction towards the Earth. Beta=0 corresponds to the Galactic plane. k) Delay time distribution of arriving particles normalized to 1.

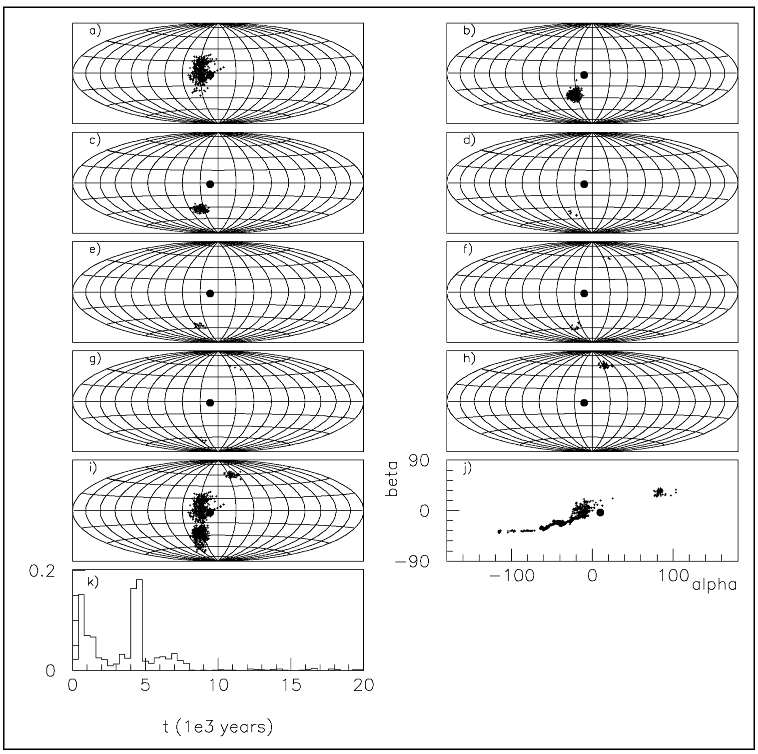

Fig. 2. As in Fig. 1 but for protons with energy 3×10^{18} eV. Maps from a) to h) show directions of particles arriving with consecutive time delay intervals of 3×10^3 yr.

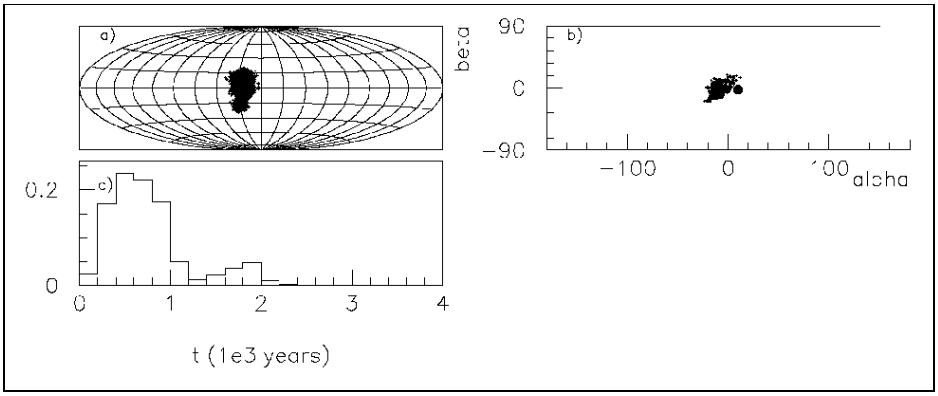

Fig. 3. Graphs for protons with energies 4×10^{18} eV which reached the Earth. a) Arrival directions integrated over time; b) injection direction distribution (as in Fig. 1j); c) time delay distribution.

We have followed numerically proton trajectories ejected isotropically from the source situated 8.4 kpc away from us towards the AGASA excess. Those which hit the 250 pc sphere around the Earth are counted and their arrival directions are presented in Figs. 1,2,3 for 10^{18}, 3×10^{18}, and 4×10^{18} eV, respectively, to correspond with the AGASA energy region.

4 Conclusions

We have considered the propagation of protons with different energies in the Galactic magnetic fields assuming as an example that a discrete source is located at the distance of the Galactic Center and in the direction of the AGASA excess at the energy $\sim 10^{18}$ eV. It is found that the image of the point like source may be completely different even if the proton energies do not differ significantly. For example arrival directions of the youngest bulk of particles are shifted by $\Delta l \cong 10^{o}$ with mean b not much changed (see Figs. 2 and 3). Thus, if the source were exactly in the GC, then the arrival directions would probably coincide with the observed AGASA source. However, at later times and energy 3×10^{18} eV two images of the proton source appear at completely different locations, each with relatively small angular extent. They mimic the appearance of discrete sources of EHE protons at directions where no source is present. The image of a single source depends on the observation time after the instantaneous injection of particles. If proton energies are reduced to 10^{18} eV, then again the picture changes significantly. In this case injected protons arrive to the Earth from almost half of the sky for a long time after proton injection. At these energies the information about the true location of the proton source is lost (see Fig. 1), although the arriving directions are far from isotropic.

It is found that our results do not depend on the particular distribution of the irregular magnetic component. Note that the effects observed at specific energies scale linearly with the adopted magnitude of the magnetic fields. Therefore, observed anisotropy discussed in our paper at slightly different energies could give independent information about the magnitude of the regular magnetic field in the Galaxy.

The number of protons which arrive to the Earth from the 'AGASA source' can be estimated from the flux 9×10^{-14} m^{-2} s^{-1} derived from the SUGAR observations (Bellido et al. (2001). It is $\sim 7.4 \times 10^{28}$ particles s^{-1}, for the source located at the distance of 8.4 kpc. Using the results of our trajectory calculations we can find the ratio of the number of particles arriving to the Earth at specific times to the total number of the injected particles (see Fig. 2 k). This allows us to estimate the fraction ξ of the rotational energy which has to be lost by a young pulsar on acceleration of protons above $\sim 10^{18}$ eV. For the pulsar with initial period 3 ms and moment of inertia $I = 1.4 \times 10^{45}$ g cm^2, fraction of the total rotational energy of the pulsar to be converted to relativistic protons at 10^{18} eV is $\xi \sim 0.04 - 0.26$ (depending on the time after explosion).

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