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Propagation of ultra-high energy cosmic rays in the Galaxy

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Abstract. We follow the trajectories of ultra-high energy cosmic rays in the regular and random Galactic magnetic fields. The time spent by these particles in the Galactic plane indicates the possible locations of their acceleration sites, assuming that the detected cosmic rays are of Galactic origin.

1 Introduction

The observation of atmospheric showers with total energy above $\sim 5 \times 10^{19}$ eV constitutes a clear evidence for the absence of the predicted Greisen-Zatsepin-Kuzmin cutoff in the Ultra High Energy Cosmic Ray (UHECR) spectrum (Zas, 2001). A possible solution to this puzzle is that the sources of the UHECRs are closer than a few tens of Megaparsecs to our Solar System, which is the typical absorption length for proton photoproduction in the Cosmic Microwave Background at these energies. Several models and ideas have explored this possibility, some of them claim that the sources of the observed highest energy events could well be in our own Galaxy. For example the model of Blasi *et al.* (2000) predicts that UHECRs are mostly iron nuclei accelerated in young strongly magnetized neutron stars in our Galaxy. Cannonballs in the Galaxy (Dar *et al.*, 1999) are also a possible candidate. In another class of models the UHECRs are produced in the decay of superheavy relics created in phase transitions in the early universe which accumulate in the halo of our Galaxy (Berezinsky *et al.*, 1997), see also Bhattacharjee *et al.* (2000) for a review. A model has also been proposed in which the UHECRs are produced by the decay of Z^0 bosons originated in collisions of UHE neutrinos with the cosmic neutrino background (Weiler, 1999). A characteristic signature of these halo scenarios is the presence of an anisotropy in the arrival directions of the highest energy events as a consequence of the offset of the Solar System from the Galactic center. The study of the deflections of these particles in the Galactic Magnetic Field (GMF) is then of special relevance to test the proposed Galactic and Galactic halo models (Medina-Tanco *et al.*, 1998). Even if the sources of the UHECRs turn out to be extragalactic, the determination of how much the GMF deflects their trajectories is essential to correlate their arrival directions with the parent sources. Another interesting aspect of this study is that if a point source is identified with high statistics, the energy dependent deviation of the particles in the GMF could lead to a better understanding of its structure and magnitude.

In this paper we investigate the propagation of UHECRs in the regular as well as random components of the GMF. We have performed 3-D simulations of the propagation of CRs as a function of their rigidity (momentum/charge) and we have concentrated our study on determining their propagation in the Galactic plane since this is where the sources of Galactic cosmic rays are expected to be concentrated.

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2 Propagation of CRs in the GMF

We have used two extreme combinations of the currently available models of the regular component of the GMF, which incorporate the knowledge obtained from experimental observations: (i) a bisymmetric spiral field model with field reversals in the Galactic arms and odd parity when the Galactic plane is crossed (BSS-A) and (ii) an axisymmetric spiral field with no reversals and even parity (ASS-S). The magnitude of the regular field is $6.4\ \mu$G at $r = 4$ kpc Galactic radius, decreasing as $1/r$. The GMF is very uncertain in the region $r < 4$ kpc around the Galactic center, so we keep the field strength constant there. There is no z component of the field in these models. On top of them we include a random GMF of typical magnitude a factor 2 smaller than the regular component and coherence length 100 pc. More details of the models can be found in Stanev (1997).

We perform two different types of propagation with different purposes. We backtrack "anti-cosmic rays" injected at the Earth at different Galactic latitudes and longitudes until they reach a Galactic radius of 20 kpc. The purpose is to investigate the locations of the Galactic sites where CRs observed at the Earth might possibly come from. We also inject cosmic rays at different points in the Galactic plane and track their trajectories until they reach $r = 20$ kpc. The aim here is to understand how CRs pass through the two mod-

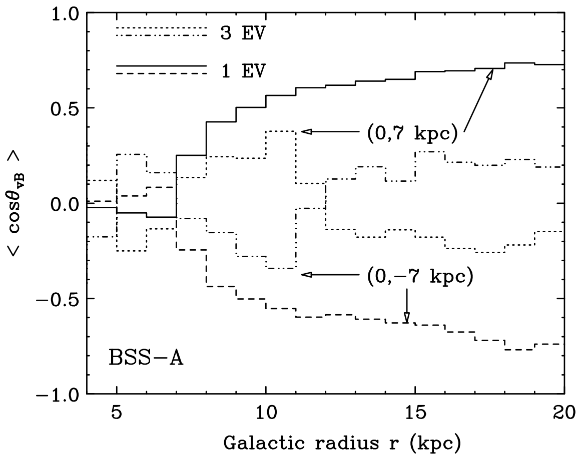

Fig. 1. Average value of the cosine of the angle between the CR track and the BSS-A GMF ($\langle \cos \theta_{vB} \rangle$) as a function of Galactic radius for CR tracks within ± 100 pc of the Galactic plane. The result for CR rigidities 1 and 3 EV and for CRs injected at positions $(x_{\rm G}, y_{\rm G}) = (0, 7 \text{ kpc})$ and $(0, -7 \text{ kpc})$ in the Galactic plane are shown. The random component of the GMF has been set to zero.

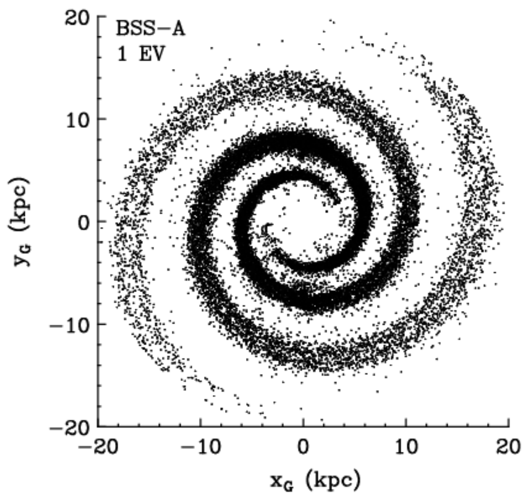

Fig. 2. Positions of the points where the CRs cross the Galactic plane. 400 CRs of rigidity 1 EV are injected at each position $(x_{\rm G}, y_{\rm G}) = (0, 7 \text{ kpc})$ and $(0, -7 \text{ kpc})$ in the Galactic plane. The random component of the GMF has been set to zero.

els of the GMF we are using. Energy losses of CRs are not taken into account since they are negligible along the distances they propagate, typically less than 2 Mpc at rigidity of 0.05 EV (1 EV $= 10^{18}$ V).

We have propagated particles of rigidity between 0.02 EV and 5 EV. The propagation of particles of rigidity smaller than ~ 0.01 EV requires a diffusion treatment which we do not address in this paper. We have calculated that for rigidities greater than 5 EV, less than 20% (12%) of the CRs injected from the Earth cross the Galactic plane in the BSS-A (ASS-S) model and hence a large sample of CRs has to be simulated to arrive to any conclusion.

2.1 Propagation from the Galactic plane

As a first exercise, we set to zero the random component of the magnetic field in our calculations and we concentrate on the study of the CR propagation under the influence of the regular magnetic field only. In figure 1 we show $\langle \cos \theta_{vB} \rangle$, the average value of the cosine of the angle between the CR track and the BSS-A GMF as a function of Galactic radius for CR tracks within ± 100 pc of the Galactic plane. This is a way to quantify to which extent the CRs propagate following the GMF lines. To produce this plot, CRs of different rigidities are injected in all directions from two positions in the Galactic plane, $(x_{\rm G}, y_{\rm G}) = (0, 7 \text{ kpc})$ and $(0, -7 \text{ kpc})$ which sit roughly in the middle of each of the Galactic magnetic arms. It is clear from fig. 1 that the CRs follow the GMF lines. $\langle \cos \theta_{vB} \rangle$ has opposite sign when CRs are injected in opposite points with respect to the Galactic center due to the reversal of the GMF in the BSS-A model. One can also see that at the injection point ($r = 7$ kpc), $\langle \cos \theta_{vB} \rangle \sim 0$ as expected since the injection directions are sampled from an isotropic distribution. For any of the injection points $\langle \cos \theta_{vB} \rangle$ changes sign at $r = 7$ kpc indicating that CRs are travelling inwards to the Galactic center and outwards to the edge of the Galaxy. Particles with higher rigidity are less affected by the GMF and they have lower values of $\langle \cos \theta_{vB} \rangle$ as can be seen in figure 1. For illustrative purposes we show in figure 2 the positions of the points where the CRs cross the Galactic plane at rigidity 1 EV. Including the random component of the GMF decreases $\langle \cos \theta_{vB} \rangle$ from ~ 0.53 (~ 0.67) to ~ 0.37 (~ 0.41) at $r = 10$ kpc ($r = 15$ kpc) for rigidity 1 EV and injection at (0,7 kpc), but its behavior as a function of Galactic radius exhibits the same features as when the random field is set to zero.

The whole picture changes completely in the ASS-S model. The value of $\langle \cos \theta_{vB} \rangle$ in this case is close to zero for all Galactic radii. The reason for this is that the fields in the ASS-S model have opposite polarities in the northern and southern Galactic hemispheres and the CRs spend on average the same time in each of them so that the positive and negative projections of their tracks along the GMF cancel each other. The ASS-S model tends to preserve the initial CR direction because the Lorentz force changes sign when the Galactic plane is crossed, so that its average along the CR track is close to zero. As a consequence the Galactic magnetic arms are no longer 'mapped' by the CR propagation and the picture is completely different from the one shown in fig. 2 for the BSS-A model.

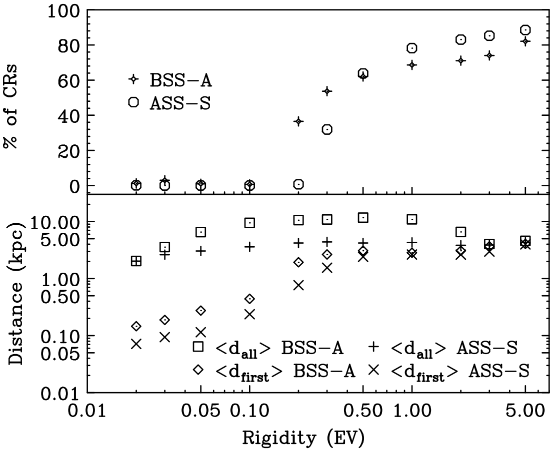

Fig. 3. Upper panel: Fraction of injected CRs that never cross the Galactic plane as a function of rigidity. Lower panel: Average distance from the Earth to the points where CRs cross the Galactic plane and average distance to the first crossing point. CRs are injected isotropically and backtracked from the Earth.

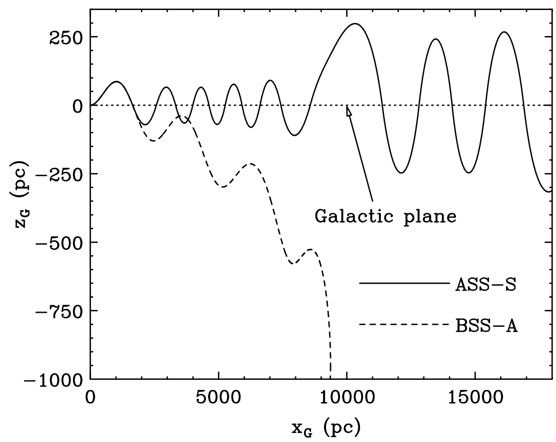

Fig. 4. Projection of a CR track onto the $x_{\rm G} - z_{\rm G}$ plane ($z_{\rm G}$ corresponds to the direction perpendicular to the Galactic plane) in the BSS-A and ASS-S models. The CR rigidity is 1 EV and it has been injected at the position $(x_{\rm G}, y_{\rm G}) = (0, -7~{\rm kpc})$ in the direction of the Galactic anticenter (Galactic latitude $0^{\rm o}$, Galactic longitude $180^{\rm o}$).

2.2 Propagation from the Solar System

In a few years all the sky will be potentially observable in cosmic rays by the present and currently under construction air shower arrays. With this in mind we have injected antiparticles isotropically in Galactic latitude and longitude from the Solar System and we have followed their trajectories in the Galaxy keeping track of the positions where they cross the Galactic plane. We have calculated as a function of rigidity, the average distance $\langle d_{\rm all} \rangle$ from the Earth to all the crossing points, the average distance to the first crossing point $\langle d_{\rm first} \rangle$ and the fraction of particles that escape from the Galaxy without crossing the Galactic plane. These quantities are useful to constrain the possible sites where UHECRs might be accelerated assuming they are of Galactic origin. The result is presented in fig. 3 for the BSS-A and ASS-S models of the GMF. The random component of the GMF is taken into account to produce this plot. Two clearly differentiated behaviors can be seen in the BSS-A case: $\langle d_{\rm all} \rangle$ has a maximum at a rigidity around 0.5 EV above which it decreases because the cosmic ray's gyroradius is large enough so that they rapidly leave the Galaxy. This conclusion is reinforced by noticing that a large fraction $\sim 65\%$ of CRs never cross the Galactic plane at rigidity 3 EV (see the upper panel of figure 3) and by the fact that the average distance to the position of the first crossing is similar to the average distance to the total number of crossings. At rigidities below 0.1 EV the cosmic rays start to exhibit a diffusive behavior and they wander around the Solar System position before leaving the Galaxy. The average distance to the first collision is then reduced significantly with respect to its value at higher rigidities and the fraction of particles that never cross the Galactic plane is only $\sim 4\%$ at 0.1 EV. The ratio of the two distances shown in the lower panel of fig. 3 is proportional to the average number of crossings and it clearly follows the inverse pattern shown in the upper panel.

Particles of rigidity above ~ 0.5 EV also leave the Galaxy very rapidly in the ASS-S model. However the fraction of particles that never cross the Galactic plane is smaller than in the BSS-A model for rigidities between 0.1 and 1 EV. This is due to the odd parity of the magnetic field present in the ASS model which tends to trap the particles in the Galactic plane. This tendency is not present in the BSS-A model due to the even parity of the magnetic field. This is nicely illustrated in figure 4 which shows a portion of the projection of a CR track onto the $x_{\rm G} - z_{\rm G}$ plane ($z_{\rm G}$ being the direction perpendicular to the Galactic plane) in the ASS-S and BSS-A models (see fig. 4 caption for details).

An interesting conclusion can be drawn from Fig. 3. Within the BSS-A model, the Galactic center (8.5 kpc from us) is slightly disfavored as the site where CRs of rigidities smaller than 0.1 EV or greater than 1 EV are accelerated. If CRs of these rigidities are of Galactic origin they have to be produced at $\langle r \rangle \sim 5$ kpc from us. It is very suggestive that the rigidity range where $\langle d_{\rm all} \rangle > r_{\rm SS} = 8.5~{\rm kpc}$ is compatible with the energy range, around ~ 1 EeV, in which AGASA (Hayashida *et al.*, 1999) observes an excess of particles from the Galactic center. The excess disappears quickly at higher energies. In the ASS-S model the Galactic Center is disfavored as the source of the UHECRs for all the rigidities in the range we have explored.

To further investigate the possible relation between the propagation through the BSS-A model and the anisotropy observed by AGASA, we have injected particles isotropically from a ring of radius $r = 4$ kpc in the Galactic plane around the Galactic Center and we have propagated them through the BSS-A field. We keep track of the points where the CRs cross the Galactic plane and we join them for each of the individual particles we have propagated. This gives us a first

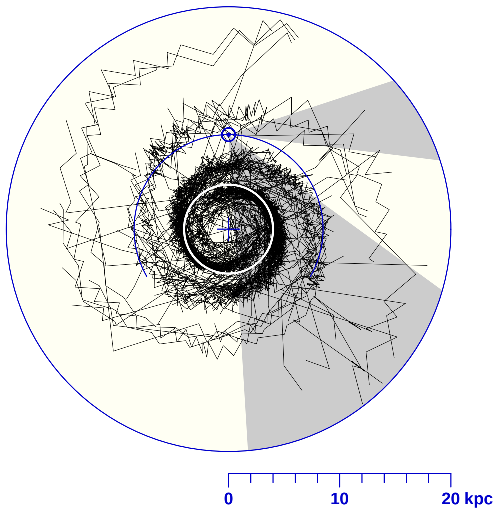

Fig. 5. Trajectories of 1 EV particles injected isotropically at the 4 kpc circle (BSS-A model). See text.

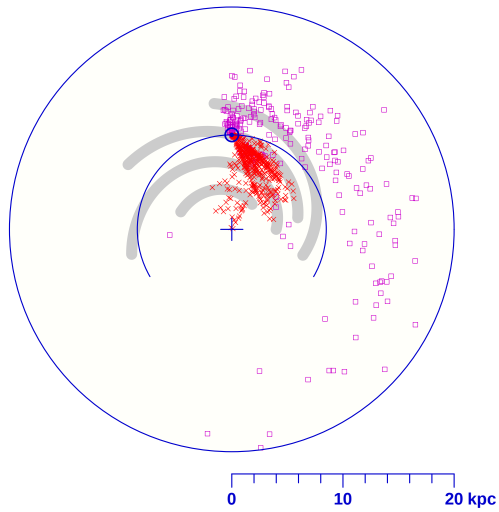

Fig. 6. Location of crossings of the Galactic plane of 40 to 100 EeV iron nuclei injected in the field of view of AGASA. Squares are for the BSS-A model and the x-ses for the ASS-S model with random field.

approximation to their tracks which are shown in figure 5. The two directions in which AGASA sees an excess of cosmic rays are shaded. There is a clear flow of particles towards the AGASA field of view, however we cannot derive any conclusion about the directions at which the events arrive at the AGASA detector because the CRs wind around the direction of the magnetic field in such a way that the actual direction when they arrive at the Earth could even be perpendicular to the field.

2.3 Application to a specific model.

The model of Blasi *et al.* (2000) is very attractive as it does not require extreme conditions at the source and accelerates iron nuclei up to 100 EeV with a flat $1/E$ spectrum. These iron nuclei are in the rigidity regime of 1 to 4 EV, where the influence of the GMF is very significant. To determine the possible location of these sources we inject iron nuclei with energy between 40 and 100 EeV from the field of view of the AGASA experiment and follow their propagation in the Galaxy. Fig. 6 shows the crossings of the Galactic plane by these iron nuclei. The BSS field leads the cosmic rays away from the Galactic center, mostly in the direction of the Perseus arm. Once the nuclei reach the arm, they generally follow the direction of the field. 30% of all nuclei cross the Galactic plane, and the average number of crossings for these nuclei is 1.5. In the ASS model the iron nuclei cross the plane in the direction of the Orion and Sagittarius arms and the Galactic center. Only about 20% of all injected Fe nuclei cross the Galactic plane, but once they do, the average number of crossings is 4.7. The ASS model is more favorable to Blasi *et al.* (2000), since it leads the iron nuclei to a region with higher stellar population.

3 Outlook

We plan to update the GMF model and extend our calculations to study the anisotropies associated with different distributions of potential cosmic ray sources, both close to the Galactic plane and in the halo of the Galaxy. For this purpose a method has to be developed and implemented to efficiently propagate the particles from their sources to the vicinity of the Solar System. Otherwise, given a distribution of sources an impractically large sample of particles would have to be simulated to get a statistically significant number of hits on the Earth. The magnetic field can have a focusing or defocusing effect on a distribution of sources depending on the energy of the particles. There might for instance be sources of CRs at some locations that are invisible in a certain energy range due to the effects of the propagation in the GMF. We plan to investigate these important issues in the future.

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