Mapping the sky onto the detector using charged particles

A. Guzmán* and G. Medina-Tanco*

**Insituto de Ciencias Nucleares, UNAM, México*

Abstract. **Cosmic ray protons with energies in excess of 10^{19} eV suffer, in general, a small but yet significant amount of deflection while traversing the Galactic Halo (GH) and disk. In spite of this fact, unless the intergalactic medium contains magnetic fields tih strength of the order od μG, ultra high energy cosmic rays, still retain very valuable directional information which may help identifying their sources.**

Traditionally, the deflection suffered by incoming charged particle are calculated applying the reversibility of the trajectories in a magnetic field, i.e., injecting the antiparticle at Earth with an opposite momentum, thus finding the pointing direction at the border of the outsquirts of the Galactic field. While this procedure is useful to search for the sky coordinates of counterparts to incoming particles, it is unsuitable to generate counterparts of the true populations of astrophysical objects onto the detector. In the present work we highlight a numerical algorithm to realize the latter transformation which allows, depending on particle energy and direction on the sky, to perform an accurate mapping of a set of coordinates at the border of the Halo onto the sky detector at Earth.

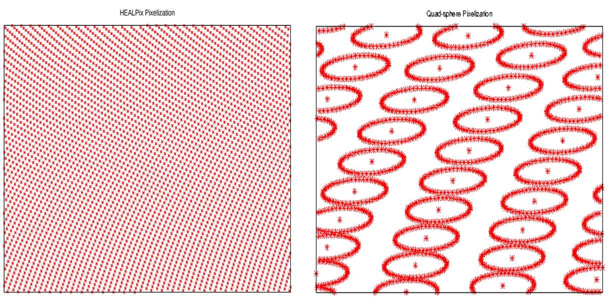
***Keywords*: Mapping Sources ExtraGalactic**

I. Introduction

The propagation of Ultra High Energy Protons (UHECR), with energies in the excess of 10^{19} eV, throughout the galaxy depends almost completely on the magnetic field present in such a large scale. Due to the lack of direct measurement of the topology and intensity of this field, a model based on rotation measurements of pulsars and extraglactic radio sources, and also based on dipersion measurements from nearby pulsars, has been built [1][4]. In order to, at least to a certain precision, properly simulate the propagation of UHECR in presence of this field, some asumptions must be made about its global large scale structure, although it is virtually imposible to know the Galactic Magnetic Field in a local scale for faraway regions in our Galaxy. With the aid of this Galactic field the particle's trayectory can be estimated injecting its antiparticle at Earth with an opposite momentum. This is the backbone of our study. First, we inject anti-protons with a momentum pointing outwards in the detector (Earth) with a very dense pixelization scheme (see [3]). Then, we propagate this particles until they reach the Galactic Halo using Galactic magnetic field, thus creating a comprehensive map of the counterparts in the Galactic Halo for each of the injected particles' direction. We do this simulation for different energies and thus build a large mapping matrix. This matrix is used to interpolate arrival directions at the external border of the Halo into the arriving directions at the detector

II. Pixelizations

Before dealing with the problem of interpolating in the sphere we conducted several tests using different pixelation schemes, namely the Quadrilateralized Spherical Cube[2] or "quad-sphere" and the more recent Hierarchical Equal Area isoLatitude Pixelization (HEALPix[1])[3]. While the quad sphere pixelization scheme was used as the standard for the Cosmic Background Explorer (COBE) it proved to have a small angular resolution and has been superseeded. Due to resolution needs of the new cosmic microwave background experiments new pixelization schemes have been developed and thoroughly optimized to be used in many other suitable areas[3]. In Fig. 1 we can see how HEALpix surpasses the qued-sphere pixelization resolution. Additionally, the "quad sphere" has some minor problems in its "corners", which do not appear in the HEALPix pixelization. On the other hand, although the HEALPix is an equal area pixelization scheme, the pixels have slightly different shapes depending on the latitude [3], but this minor setback is totally negligible, when dealing with such a small pixel size.



(a) (b)

Fig. 1. (a) An amplified portion of the sky under the HEALPix pixelization scheme (distances beteween pixels is $\sim 0.2°$). (b)Same region of the sky under the "quad sphere" pixelization scheme. For the "quad sphere" a circle of radius $\sim 1°$ has been drawn around each pixel center to accentuate its low resolution compared with (a) (distances beteween pixels is $> 2°$)

[1]http://healpix.jpl.nasa.gov

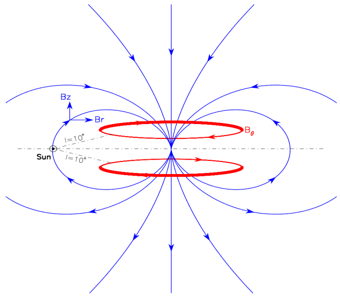


Fig. 2. A schematic diagram of the Galactic Magnetic Field model (taken from Han (2002) [1]).

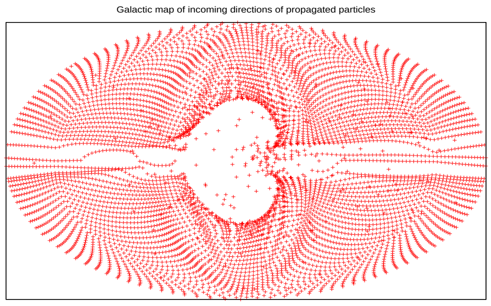


Fig. 3. An example of the several Galactic maps of propagated anti-protons produced in order to interpolate from them. In this example antiprotons were propagated from the detector with an energy of $10^{19.8}$eV.

III. Galactic magnetic field

The Galactic magnetic field we used to create the directional maps is the axisymetrical dipole field (see Han [1]) which has poloidal and thoroidal components, but for this paper's present scope its two most important characteristics are:

- It has a dipolar component parallel to the Galactic north(b=$90°$) direction.
- It is bisymmetric spiral components in the Galactic disk.

It is also worthwhile to point out that in this model the toroidal fields have opposite directions below and above the Galactic plane. Which may also result in a noticeable asymetry in the propagation directions of outgoing UHECR, (though we injectec antiprotons the latter still holds).

The dipolar component accounts for a very intense magnetic field near the central region of the Galaxy as it is proportional to $1/r^3$. Due to the intense magnetic field in the central region even at very high energies it is vitually imposible to have a small deflection for particles travelling in the central region of the Galactic disc (see Fig. 2) . As a consequence, all maps of the Galactic Halo have an apparently empty region near the center of the Galaxy.It must be noted however, that there is strong observational evidence for such high intensuty magnetic fields, in fact may have intensive manifestations in UHECR observations[4].
As it can also be readily seen in Fig. 3 the axis symetric property of this field produces a slight but distinguishable asymetry in the Galactic longitude $[l]$ of the maps produced by propagating antiprotons in the Galactic Magnetic Field near the Galactic center.

IV. Deflections

In order to attain certain resolution for the interpolated map a cualitative test was carried out to see which energies were more suitable for a meaningful interpolation. A usual result of such a map can be seen in Fig. 3. The deflection at different energies is shown in Fig. 5b.

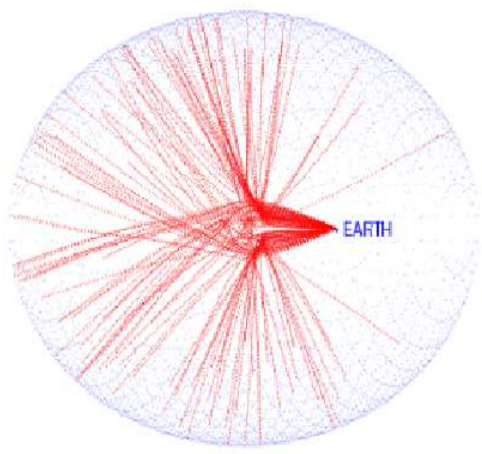
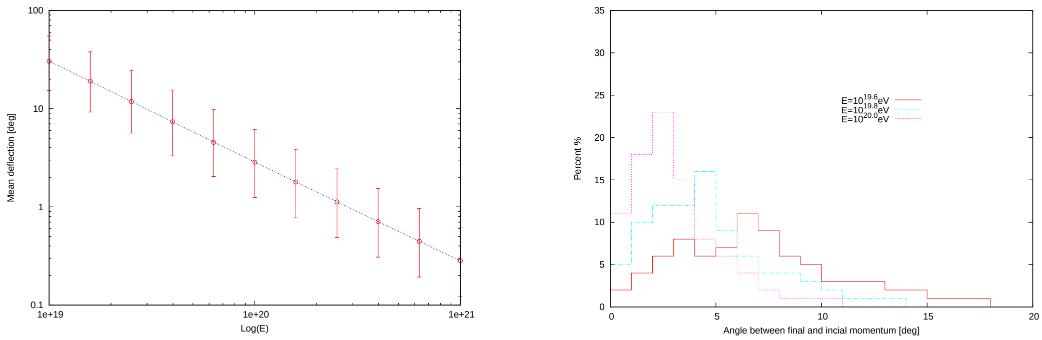


Fig. 4. Severely deflected trajectories of propagated anti-protons, which cross the inner regions of the Galaxy with $log(E) = 19.8$. The Galactic Halo Border is depicted in blue. Galactic Center is in the image's center.

As it is illustrated in Fig. 4 the Galactic center tends to bend the trayectories in very acute angles, in a way that resembles that of a lens, suggesting that protons entering the Galactic Halo in very ditinct regions can all be mapped to arrive to the Earth as if they came from the Galactic center, thus making it very difficult to seek for extragalatic sources that lay in a line of view that passes through the Galactic Center, since a significant amount of the possible incoming protons from the Galactic Halo can appear as coming from the Galactic Center.

As a complement to this study, anti-protons were injected in equal area circles from the earth, and the area deformations were studied to see if there was a significant compression or decompression of the solid angle subtended by this circles. Again there is a huge correlation between the deformation and the distance to thee Galactic Center. It is worth noticing that even at energies of $10^{19.8} - 10^{20.5}$, when the propagated map is



(a) (b)

Fig. 5. a) Mean deflections of incoming particles as a funtion of the energy b) Deflections histograms for different energies

almost identical to the injected map, a void appears in the propagated map as a result of severe deflection of the particle due to the magnetic dipole at the Galactic Center. Consequently, even if we detect protons coming from the Galactic Center it is highly improbable that this particles have an extra galactic source lying close to the line of view. There also appear to be regions of high deflection in the polar regions ($b = \pm 90$) altough the effect is much less significant in this regions, attention must be paid when interpolating in the Galactic polar regions. But as a general rule the Galactic Center must not be taken into account when interpolating coordinates from objects in the Galactic Halo. Nevertheless, it must be stressed tha even if the qualitatuve features discussed so far are quite generalquantitative statements depend strongly on the specific assumptions made about the Galactic Magnetic Field.

V. INTERPOLATION

We propagated the antiprotons through the Galaxy for energies from $10^{19.5}$eV to $10^{20.5}$eV in steps of $log(E) = 0.1$ (i.e.$10^{19.5}$eV, $10^{19.6}$eV, $10^{19.t,}$eV etc.). For each one of this energies we injected 786 432 antiprotons, (this is the size of the mesh shown in Fig. 1a) of pixels as described in II, with an outward pointing momentum. Each of these pointing to a different point in the sky, hence the "injected" map on the detector had an angular resolution of roughly $0.2°$, which, by the way, is beyond the angular resolution of most of today's working detectors. This allows us to make a thorough spatially-dense mesh to give us some insight on how extra Galactic UHECR sources may appear on the Earth's true sky. Also, because of the simple nature of the interpolation procedure, a fine mesh of points is necessary to reduce the numeric errors.

In general terms the interpolation procedure could be depicted as follows:

A huge archive with all the coordinates lying in the Galactic Halo is made for the energies $10^{19.5}$eV to $10^{20.5}$eV from antiprotons injected at the Earth and propagated with the aid of the Galactic Magnetic Field model as described in section III. For a coordinate map of objects in the Galactic Halo interpolation is carried out by means of comparing nearest neighbours in both spatial (l, b) coordinates and energy space, of this map and the above mentioned archive. Another map is then created with the interpolated coordinates of arriving directions at Earth fo the Galactic Halo UHECR "source candidadtes".

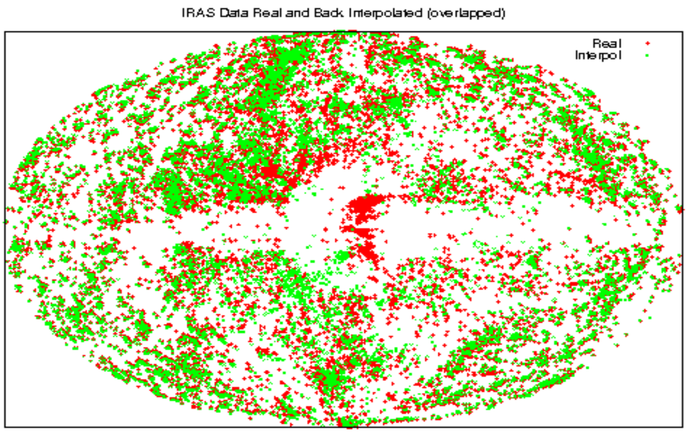
VI. INTERPOLATION ALGORITHM EXAMPLE APPLICATION

As proof of principle of the method highlighted in this article, we interpolated some objects from the IRAS PSCz [5]. Objects with available redshift and 60 μm flux, were selected up to a depth of 200 Mpc (h=0.71). This objects were used as sources of UHECR injecting an energy spectrum $\propto E^{20}$. The particles were propagated through an intergalactic magnetic field model constructed in a way consistent with distributions of luminous matter as given by the CfA Redshift Catalog [6] thus creating a map of posible extra galactic sources. Afterwards, we propagated protons (not antiprotons) from the Galactic Halo on to the surface of the detector, this is, we injected the protons into the Galactic Halo with an inward pointing momentum, with this coordinates, as if they were the extraGalactic sources of UHECR, hence creating a "back" interpolated map.

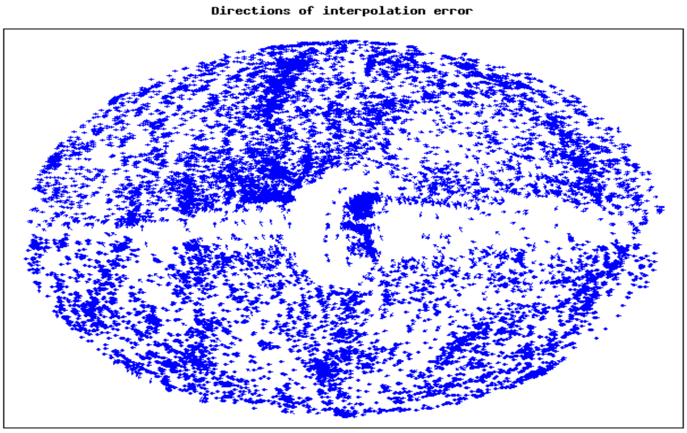
Finally we compared the results of the map of the interpolated infrared sources and the "back" interpolated map made from the propagation of UHECR through the Galaxy. The results of this simulation can be seen in Fig. 6a. Most of this coordinates is seen to overlap, hence showing that the interpolation is meaningful till a certain point. But as expected, there is a clear discrepancy between the interpolated and the "real" data for cooordinates that lay in the Galactic center. In Fig. 6b the directions of this discrepancies is shown. For clearity purposes only the direction is depicted in this figure.

VII. CONCLUSIONS

Although some improvements can still be achieved in the interpolation procedure, its proof of principle is seen to be working as expected. The refinement of the



(a)



(b)

Fig. 6. a) Interpolation “test”. In red are the extraglactic sources taken from interpoltaing the IRAS data[5].In green are shown the “back” interpolated sources. As expected ther is a significant discrepancy in sources with a line of view that goes through or nearby the Galactic center. b) Interpolation error’s directions. The size of the arrows is not related to the error’s size, they are only intended to illustrate the direction of the discrepancy between “real” and interpolated data

mesh has incremented the accuracy of the method. Work is being directed towards the definition of exclusion regions and the mathematical assignment of a coordinate dependent accuracy.

VIII. Acknowledgements

This work is partially supported by the Mexican agencies CONACyT and UNAM’s CIC and PAPIIT. Some of the results in this paper have been derived using the HEALPix (Górski et al., 2005) package[3].

References

[1] Han, J.L., *Astrophysical Polarized Backgrounds* American Institute of Physics, edited by S. Cecchini, S. Cortiglioni, R. Sault and C. Sbarra, pp.96-, 2002. arXiv:astro-ph/0110319v1

[2] O’Neill, I.M. and Laubscher, R.E. 1976., *Extended Studies of a Quadrilateralized Spherical Cube Earth Data Base*, Computer Sciences Corp., EPRF Tech. Report 3-76.

[3] Górski, K.M., E. Hivon, A.J. Banday, B.D. Wandelt, F.K. Hansen, M. Reinecke, and M. Bartelmann, *HEALPix: A Framework for High-resolution Discretization and Fast Analysis of Data Distributed on the Sphere*,Ap.J., 622, 759-771, 2005. http://healpix.jpl.nasa.gov

[4] G.Medina-Tanco, A.G.O. Krone-Martins, Nuclear Physics B (Porc. Suppl.) 165(2007) 280-286

[5] W.Saunders, W.J.Sutherland, S.J.Maddox, O.Keeble, S.J.Oliver, M.Rowan-Robinson, R.G.McMahon, G.P.Efstathiou, H.Tadros, S.D.M.White, C.S.Frenk, A. Carraminana, M.R.S.Hawkins,*The PSCz Catalogue*,Mon.Not.Roy.Astron.Soc. 317 (2000) 55 arXiv: astro-ph/0001117v2

[6] Medina-Tanco, G.A. 1999 Astrophysics, J.Lett. 510 L91.