Time Delay, Deflection Angle and the Possible Origin of the Highest Energy Cosmic Rays

PANTEA DAVOUDIFAR
Research Institute for Astronomy & Astrophysics of Maragha
dfpantea@riaam.ac.ir
DOI: 10.7529/ICRC2011/V02/1183

Abstract: Time delays of Cosmic Rays (CRs) have been the subject of many researches in different fields. Cosmic rays with the highest energies propagate in their paths with small deflections relative to the straight line propagation of light. The supposed structure of magnetic fields: galactic, intergalactic and the large scale cluster magnetic fields, has an important role on the deflection angles and the time delays of the highest energy particles. In the present work using a simulation based on Auger events and suggestions about magnetic fields, discuss about the range of deflection angles and the resulted time delays which is important on identifying the origin of CR particles.

Keywords: Cosmic rays, Galaxies: magnetic fields, Magnetic fields.

1 Introduction

In the recent decades, detection of CRs with measured energies beyond the Greisen-Zatsepin-Kuzmin cutoff (i.e. GZK cutoff) [1] has been of special interest [2]. Considering the observed Auger events, the arrival directions of highest energy particles at the Earth first supposed to be correlated with the direction of those Active Galactic Nuclei (AGN) found within 75 Mpc of the Galaxy [3, 4]. However this result has been the topic of many debates, for instance it has been suggested that the correlation is best for AGN with hard X-ray fluxes [5] or that a better correlation may be with FR I/II radio galaxies with large jets [6]. More recently, the number of Auger high energy events increased and a more precise measurement made possible [7]. As soon as an astronomical object considered being the possible source of Ultra High Energy Cosmic Rays (UHECRs), new limits appear to treat the celestial magnetic fields. In the case of UHECRs, an important application to treat those magnetic fields is the particle deflections due to Galactic and Extragalactic Magnetic Fields (i.e. GMFs and EGMFs). Unlike electrons, for charged hadrons deflection is more important than synchrotron loss in the EGMF. A relativistic particle of charge qe and energy E, has a gyroradius $r_g \approx E/(qeB_\perp)$ where $B_\perp$ is the field perpendicular to the particle momentum. For the EGMFs it is usual to consider propagation distance D much smaller than r_g, then deflection caused by the random field with strength B and correlation length L_C is $\propto \sqrt{B^2 L_c}$ for a fixed distance D [8 and 9]. If the extragalactic magnetic fields and the sources of these CRs are coupled with matter, it is possible that the deflection angle is larger than expected in the case of a uniform source distribution due to effectively larger fields [10]. A further analysis may yield a correlation with a larger deflection angle and/or more distant sources, even another possibility is that the cosmic ray sources are not those specific AGN, but the sources simply follow the overall sky distribution of the AGN, the super-galactic plane [3 and 11], whilst it must be considered that investigating the correlation of Ultra High Energy Cosmic Rays (UHECRs) with AGN based catalogues may be tricky [10].

2 Possible Sources of UHECRs

Cosmic rays extend over a huge range of energies. For a CR iron nuclei it is possible that inside Supernova Remnants (SNRs) accelerates up to $\sim 10^{17} eV$ [12]. Models for Magnetohydrodynamic (MHD) turbulence suggests that protons could be accelerated up to $10^{17} eV$ and heavy ions above $10^{18} eV$ [13]. It suggests that the transition from galactic to extragalactic component takes place in energy range 10^{17} -$10^{18} eV$. Above $10^{18} eV$ [12] our galaxy seems to be incapable of accelerating particles to the necessary energy and it is assumed that higher energy particles are dominated by extra-galactic ones. The most recent observations of UHECRs are Auger air showers [3, 4, and 7] with energies above ~ 57 EeV (i.e. $57 \times 10^{18} eV$).
At the highest energies, the nature of cosmic ray sources is not known but it is suggested that this acceleration

might be either close to massive black holes [14] or in the large scale outer jet magnetic fields of AGN [15]. It is usual to consider diffusive shocks as an important mechanism of CR acceleration; this process is rather slow [16] and requires a stable shock front, or at least a stable magnetic containment region. The lifetimes of sources and substantial magnetic lobe structures are of special importance in this case. For acceleration in the vicinity of a central black hole (with a large potential gradient), presumably an active black hole environment is required where it is suggested that a hard x-ray emission might be an indicator of candidate sources [17]. Sigl, Schramm, & Bhattacharjee [18] showed that in an AGN or a rich galaxy cluster bellow around 100 *Mpc* away, it is possible that protons with the energies ~ 3×10^{20} *eV* produced by the standard mechanism of diffusive acceleration in the relativistic shocks. They calculated the arrival direction of such proton have to be within around 15 degrees in the direction of their sources.

In 1993 Rachen & Biermann [19] presented a model of the origin of ultra high energy cosmic rays above about 1 *EeV*, assuming hot spots in FR-II radio galaxies as their sources and diffusive shock acceleration as the mechanism how they attain their energy. Continuing their calculation, Protheroe & Johnson [20] showed that the accompanying intensities of gamma rays and neutrinos are not in conflict with the observations. Nagar & Matulich [6] in a detailed investigation mentioned that the radio galaxies are significant sources of UHECRs. It is also mentioned that no clear correlation is seen between UHECRs and supernovae, supernova remnants, nearby galaxies, or nearby groups and clusters of galaxies. Nagar & Matulich [6] deduced that the nearby extended radiogalaxies are the most likely sources of at least some UHECRs detected by Pierre Auger Observatory and the remaining UHECRs are not inconsistent with an isotropic distribution; their correlation to nearby AGNs is much less significant that earlier estimated.

2.1 The Source Lifetime

In 1968 scientists come to a general agreement that the Seyfret galaxies have the total lifetime at between 10^8 and 10^{10} *years* depending upon the fraction of spirals [21]. Then, Sanders suggested the minimum statistical lifetime of $3.5-7\times10^8$ *years* [22] where the radio continuum jets in the central regions of Seyferts could constrained the lifetime of individual Seyfert episodes to be shorter than 10^6 *years*.

AGN remain in an active state for an unknown period of time, with the lifetimes which is not believed to be large compared to the evolutionary lifetimes of many astrophysical objects. Estimates of AGN lifetimes range roughly from 10^6 *years* to 10^9 *years* [23].

The "statistical" lifetime of AGN, ~ 10^9 *years,* is estimated from the relative numbers of Seyfert and elliptical galaxies. The lifetimes of radio galaxies can be estimated from the dynamical processes, comparing their size and expansion rates. For low and high power radio galaxies, these "dynamical" ages are in the ranges $10^{7\text{-}8}$ and $10^{6\text{-}7}$ *years* respectively. Seyfert galaxies have dynamical ages which are shorter than this and are estimated to be at or below the order of 10^5 *years* [3, 22, and 24].

3 Magnetic fields

A practical method of measuring extragalactic magnetic fields is by Faraday Rotation Measure (FRM) of linearly polarized emission of radio sources [25]. From FRM the upper limit of B^2L_c in intergalactic space is calculated to be $BL_c^{1/2} \le 10^{-9}\,GMpc^{1/2}$ [25 and 26]. Also from baryon density [27] there is a good estimate of IGMF correlation length of 10 *Kpc* to 1 *Mpc* and too high value of *B*. Two another estimates are offered in the reviews by Knoberg [28] and Beck [29] with $B < 10^{-9} - 10^{-8}G$ without mentioning the correlation length. There are good reasons to consider the lower limit of B^2L_c to be $BL_c^{1/2} \ge 10^{-11}GMpc^{1/2}$ [30].

4 Simulation

In this research, using the random walk processes a model of GMF, IGMF and GCMF [9] used to propagate CR particles with the highest energies in different areas (i.e. Galactic, Extragalactic and Extracluster space) where the particle energies chosen to be above 57 *EeV*. The simulation consists of two parts.

I) Using the three dimensional simulated deflection of UHECRs by axisymmetric disk and halo to the Galactocentric distances of 20 *Kpc* of Medina Tanco, et al. [31], the central GMF strength is 6.4μG decaying exponentially to the larger Galactic distances. In this simulation a spiral GMF been used and the size of deflection (in degrees) is given in a Galactic coordinates (*l*,*b*) map. Having (*l*,*b*) of Auger showers, the deflection angles (i.e. θ) is obtained from the Galactic map, and using the formula (1) [8]:

$$\tau(E,d) \approx \frac{\theta^2(E,d)\cdot d}{4} \approx 1.5\times10^3 q^2 \times \left(\frac{E}{10^{20}eV}\right)^{-2}\left(\frac{d}{10Mpc}\right)^2\left(\frac{L_c}{1Mpc}\right)\left(\frac{B}{10^{-9}G}\right)^2 yr$$

the time delays of events are calculated.

II) Doing a simulation assuming the arrival direction of particles in GMF to be Galactic arrival of Auger events, (*l*,*b*) . So $x(b) = 9000/\sin(b)pc$, is the corresponding light path of the particles which travel *D* parsecs by deflections due to varying magnetic field of disk and halo of our galaxy [9 and 32 for more details]. The time delay of each event calculated as (2):

$$\tau = 3.26(D-x)years$$

where *D* is the actual path of the charged particle [9].

Using formula (1) for each shower of [7], B^2L_c is calculated. An effective Galactic *B* considered as [9, with a correction due to 7] (3):

$$B_{eff} = 0.321B_0$$

which is used in the simulation to calculate the distribution of L_c for a given B_0.

5 Results

The results of time delay distribution in GMF [9] with a correction due to [7] shows the average value of 59.8 ± 71 *years* negligible compare to minimum time delays in IGMF (i.e. 3500 *years*). Considering the possible sources of Auger events [7] B^2L_c calculated from formula (1) and has a value of ~3.5×10^{-18} G^2Mpc, and it is seen that the effect of GMF on effective B^2L_c (Galactic and Extragalactic) increases with decreasing energy and the maximum of this effect is about 14% which is negligible on the observed B^2L_c [9, 25].

Using formula (3) and observed Auger parameters of [7] in formula (1) the Distribution of L_c for a given B_0 is obtained. The best value of B_0 and L_c calculated to be $B_0=(5.18\pm2.65)\mu G$ which is consistence with the value of a few micro-gauss increasing towards inner Galaxy [33] and $L_c = \left(448^{+322}_{-101}\right)pc$ in agreement with the result of FRM of halos of galaxies [33].

The typical error on average B of Auger showers [7] is calculated ($B=(5.1\pm2.3)10^{-9}G$) and considering the value of 3.5×10^{-18} G^2Mpc for B^2L_c, the reported value of average B is 1-10nG [see also 9].

To have a clue about the possible origin of UHECRs, the source distance of 50*Mpc* and particle energy of 70*EeV* is considered. Also $B_{IGMF} \approx 2nG$ and $L_c \approx 0.45Mpc$ is considered based on calculated results.

The simulated time delay distribution of UHECRs relative to light in G, IG and GCL regions are calculated and presented. A typical time delay in G, IG and GCL magnetic fields is calculated to be $10, 10^5$ and 10^7 *years* respectively. Also an improved estimation of magnetic strength of G and IG fields and their correlation lengths [due to 7] are obtained to be [$(5.22\pm2.25)\mu G$, $(482\pm32.3)pc$] and [$(2.12\pm1.22)nG$, $(471\pm170)Kpc$] respectively. It is found that B_{GMF} towards the inner Galaxy is higher than anti center as expected. The resulted average time delay of about 10^7 *years* (even by inputting a much higher strength of $B_{GCL}=0.5G$), showed that a typical Galaxy time delay is negligible as expected. As AGN power also last about 10^7 *years* or longer [34] and being a continuous source, AGN considered as a possible source of UHECRs. On the other hand, the correlation between Auger UHECR events and AGN results a short time delay in IGM about 10^5 *years* reflecting a bursting source. The combined result could conclude a bursting over a continuous source, which consistence with the previous prediction of Farror [34]. The result is in the favor of bursting showers over a continuous cluster source.

In fact, for the sources to really be AGN and have a strong correlation, the CR delays behind directly propagating light must be much less than the lifetime of the source. With likely upper limit source lifetimes of order 100 *Myr*, turbulent intergalactic magnetic fields with strengths above 100 *nG* would seem to be excluded (Figure 1). Using Auger parameters of [7] deviation angle resulted to be ~ 10° and more.

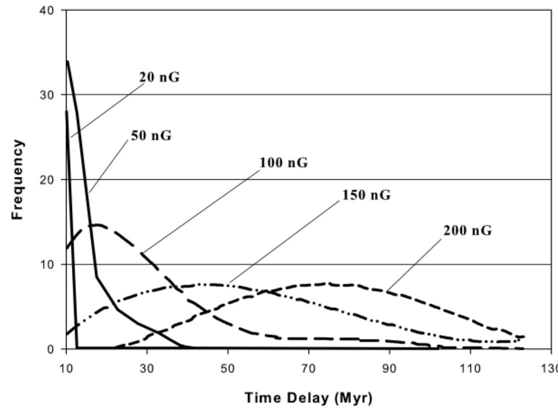

Figure 1: The simulated time delay distribution of Auger showers for various Intergalactic Field Strengths (16 *Kpc* turbulence scale, 50 *Mpc* total path length typical source distance, and 50 *EeV* protons start propagation from randomly selected positions). It is seen that the number of detectable events reduces when the strength considered for IGMF increases. Conclusion: One of the inputs is the strength of B_{IGMF} which are given from 20nG to 200nG. For higher B we would have higher time delays. The calculated average time delays of Auger showers is of order ~10^5 *years* (0.1 *Myr*), so from Figure 1, $B < 20nG$ is resulted. Also it is expected that the time delays of showers to be less than the life time of the their sources, so from Figure 1 concluded that $\tau \leq 100$ *Myr* (life time of a typical source) and $B \leq 100$ *nG* , therefore $B > 100$ *nG* is excluded (which is correspond to τ larger than 100Myr).

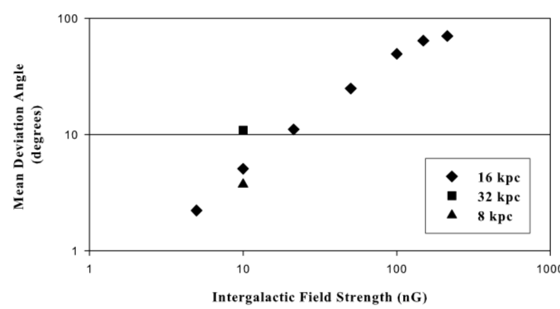

Figure 2: Propagation through a Turbulent Intergalactic Field (various turbulence scale lengths) for 50 *EeV* protons from a typical source at 50 *Mpc*. Conclusion: It is seen that for an about 10 nanogauss IGMF (without a cluster field), the mean deviation is most when the turbulence scale considered being 32 *Kpc*. The figure shows that for a mean deviation angle of a few degree the turbulence length is about 10 *Kpc* or the deviation angle is higher than what reported for the Auger showers (i.e. 3.2°). It means that the field tends to be more turbulent for the lower mean Auger deviation angles or the field is less turbulent for higher deviation angles.

If Auger project cosmic ray arrival directions considered being correlated strongly with sources up to distances of 70 *Mpc*, or even if they are correlated just with the supergalactic plane, total directional deviations must be less than (or much less than for point sources) 10°. This limits the average intergalactic field strength to below 100 *nG* and probably below 20 *nG* for most likely turbulence scales (8, 16, 32 *Kpc* shown in Figure 2). The result shows an upper limit closer to 10 *nG* (20 *nG* , if assumed that the sources must be within the supergalactic plane).

6 References

[1]. Greisen K., Physical Review Letters, 1966, **16**(17): 748-750; Zatsepin G. T., & Kuzmin V. A., Journal of Experimental and Theoretical Physics: Letters, 1966, **4**: 78-79

[2]. Rachen J. P., Stanev T., & Biermann P. L., Astronomy & Astrophysics, 1993, **273**: 377-382; Bird D. J., et al., The Astrophysical Journal, 1995, **441**: 144-150

[3]. The Pierre Auger Collaboration, Science, 2007, **318**(5852):938-943

[4]. The Pierre Auger Collaboration, Astroparticle Physics, 2008, **29**(3):188-204

[5]. George M. R., et.al, Monthly Notices of the Royal Astronomical Society: Letters, 2008, **388**: L95-L63

[6]. Nagar N. M., & Matulich J., Astronomy & Astrophysics, 2008, **488**(3): 879-885

[7] The Pierre Auger Collaboration, Astroparticle Physics, 2010, **34** (5): 314-326

[8]. Miralda-Escude J., & Waxman E., The Astrophysical Journal, 1996, **462**: L59-L62; Waxman E., & Coppi P., The Astrophysical Journal, 1996, **464**:L75-L78; Waxman E., & Miralda-Escude J., The Astrophysical Journal, 1996, **472**:L89-L92; Bhattacharjee P., & Sigl G., Physics Reports, 2000, **327**:109-247

[9] Davoudifar P., et.al, Journal of Sciences, Islamic Republic of Iran, 2011, **22** (1): 75-84

[10]. Moskalenko I. V., et al., The Astrophysical Journal, 2009, **693**:1261-1274

[11]. Stanev T., et.al, Physical Review Letters, 1995, **75**:3056-3059; Stanev T., 2008, arXiv: 0805.1746v2

[12]. Berezhko E. G., Advances in Space Research, 2008, **41**(3): 429-441

[13]. Bell A. R., & Lucek S. G., Monthly Notices of the Royal Astronomical Society, 2001, **321**: 433-438; Bell A. R., Monthly Notices of the Royal Astronomical Society, 2004, **353**: 550-558

[14]. Keenan D. W., Monthly Notices of the Royal Astronomical Society, 1978, **185**: 389-398; Dermer C. D., Miller J. A., & Li H., Astrophysical Journal, 1996, **456**: 106-118; Rieger F. M., & Aharonian F. A., Journal of Modern Physics D, 2008, **17**(9):1569-1575; Istomin Y. N., & Sol H., Astrophysics ans Space Science, 2009, **321**(1): 57-67

[15].Tinyakov P. G., & Tkachev I. I., Journal of Experimental and Theoretical Physics Letters, 2001, 74(9): 445-448; Lipari P., & Morlino G., Proceeding of 28th International Cosmic Rays Conference, 2003, 2683-2686; George M. R., et al., Monthly Notices of the Royal Astronomical Society:Letters, 2008, **388**: L95-L63; Muxlow T. W. B., Monthly Notices of the Royal Astronomical Society, 2011, **404**(1): L109-L113

[16]. Protheroe R. J., & Clay R. W., Publications of the Astronomical Society of Australia, 2004, **21**:1-22

[17]. George M. R., & Fabian A. C., The X-ray Universe Symposium 2008, published online at (http://xmm.esac.esa.int/external/xmm_science/workshops/2008symposium), 2008, 172

[18]. Sigl G., Schramm D. N., & Bhattacharjee P., Astroparticle Physics, 1994, **2** (4): 401

[19] Rachen J. P., & Biermann L., Astronomy & Astrophysics, 1993, **272**: 161-175

[20] Protheroe R. J., & Johnson P. A., Astroparticle Physics, 1996, **4**(3): 253-269

[21]. Woltjer L., Astronomical Journal, 1968, **73**: 914

[22]. Sanders R. H., Astronomy & Astrophysics, 1984, **140**: 52

[23] Martini P., et al., ASP Conference Series, 2003, 290: 533-534; Marecki A., Roukema B. F., & Bajtlik, S., Astronomy & Astrophysics, 2005, **435**: 427-435; Germain J., Barai P., & Martel H., The Astrophysical Journal, 2009, **704**: 1002-1020; Nesvadba N. P. H., et al., AIP Conference Proceedings, 2009, **1201**: 135-141

[24]. Ho L. C., Filippenko A. V., & Sargent W. L. W., The Astrophysical Journal, 1997, **487**:568

[25]. Kronberg P. P., Reports on Progress in Physics, 1994, **57**(4):325-382

[26]. Vallee P. J., Fundamentals of Cosmic Physics, 1997a, **19**: 1-89; Vallee P. J., Fundamentals of Cosmic Physics, 1997b, **19**: 319-422

[27]. Ryu D., Kang H., and Biermann P. L., Astronomy and Astrophysics, 1998, **335**: 19-25

[28]. Kronberg P. P., Astronomische Nachrichten, 2006, **327**(5/6): 517

[29]. Beck R., Revista Mexicana de Astronomia y Astrofisica, 2009, **36**:1-8

[30]. Cohen E., and Piran T., The Astrophysical Journal, 1995, **444**: L25-L28

[31]. Medina Tanco G. A., de Gouveina Dal Pino E. M., & Horvath J. E., The Astrophysical Journal, 1998, **492**, 200-204

[32]. Stanev T., Seckel D., and Engel R., Physical Review D, 2003, **68:** 103004

[33]. Strong A. W. Moskalenko I. V., and Reimer O., The Astrophysical Journal, 2000, **537**(2): 763-784

[34]. Farror G. R., Proceedings of the 30th International Cosmic Ray Conference, 2008, **2**: 161-164