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Time Delays in Cosmic Ray Propagation

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Abstract

Cosmic Rays (CR) travel at speeds essentially indistinguishable from the speed of light. However whilst travelling through magnetic fields, both regular and turbulent, they are delayed behind the light since they are usually charged particles and their paths are not linear. Those delays can be so long that they are an impediment to correctly identifying sources which may be variable in time. Furthermore deduction of CR sources without knowing CR time delays is not possible, so the magnitude of such delays will be discussed and compared to the characteristic time variation of possible cosmic ray sources.

Keywords: Cosmic rays; ISM: Magnetic fields; Galaxies: general

Introduction

Cosmic rays are energetic charged particles which propagate to us through Galactic and Intergalactic Magnetic Fields (GMF and IGMF). It has recently been shown that cosmic rays with the highest energies have arrival directions at the Earth which correlate with the directions of those Active Galactic Nuclei (AGN) which are to be found within 75 Mpc [1,2]. The exact meaning of this result has been the topic of particular debate. For instance, it has been suggested that the correlation is best for AGN with hard X-ray fluxes [3,4] or that a better correlation may be with FR I/II radio galaxies with large jets [5]. The distance of 75 Mpc was derived from the data themselves but it does represent a reasonable limit to the source distances since such particles interact with the 3°K Cosmic Microwave Background (CMB) and lose energy with a characteristic distance of that order (i.e. GZK effect). It is also mentioned that more extensive analyzes have to take into account the details of AGN radio morphology and spectral properties and may yield a correlation with a larger deflection angle and/or distant sources [6] and is also possible 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 [1,7,8].

If we do assume that the cosmic rays are from the identified AGN, we can readily put limits on parameters of the GMF and IGMFs. These limits correspond to a combination of the magnetic field strength, B , and its characteristic turbulence scale (i.e. correlation length L_c) which are entangled with the concept of “The Time Delay”. It also must be considered that, investigating the correlation of Ultra High Energy Cosmic Rays (UHECRs) with AGN based on some given particular AGN catalogs may be tricky [6].

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Materials and Methods

Cosmic Ray Sources

Cosmic rays extend over a huge range of energies. At the lowest energies conventionally studied, CRs can be of stellar origin. For instance, it is known that our Sun produces particles in flaring events. Those particles may be energetic enough to be detectable at "ground level enhancements". At higher energies (to about $10^{14} eV$ particle energy) CRs could be accelerated in Supernova Remnants (SNR) through the mechanism of diffusive shock acceleration [9]. For a CR iron nuclei it is possible that inside SNRs accelerates up to $\sim 10^{17} eV$ [10] and a model for Magneto-Hydrodynamic (MHD) turbulence suggests that protons could be accelerated to $10^{17} eV$ and heavy ions above $10^{18} eV$ [11,12]. It suggests that the transition from galactic to extragalactic component takes place in energy range $10^{17} - 10^{18} eV$ which is a good reason to use UHECRs of Auger showers with energies more than $57\, EeV$ (i.e. $57 \times 10^{18} eV$).

Above $10^{18} eV$ [10] 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. At the highest energies, there is an evidence for source directions being correlated with the super-galactic plane so those particles must be dominantly extragalactic in origin [1,7,8].

The nature of the cosmic ray sources is not known at the highest energies but basic physics tells us that any acceleration process which is progressive (not a single acceleration through a $10^{20} V$ potential), must have magnetic field containment within large scale conventional fields of very strong fields [13] as the acceleration process progresses. Suggestions are that this acceleration might be either close to massive black holes or in the large scale outer jet magnetic fields of AGN.

It is usual to think of CR acceleration being through diffusive shock acceleration. This process is rather slow [9] and requires a stable shock front, or at least a stable magnetic containment region. Source lifetimes and substantial magnetic lobe structures are clearly important in this case. If acceleration is in the vicinity of a central black hole through a large potential gradient, then one presumably requires an active black hole environment and it has been suggested that hard x-ray emission might be an indicator of candidate sources [4].

AGN Lifetimes

AGN remain in an active state for an unknown period of time, but their lifetime 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 $10^{9}\, years$. Further, AGN are well known to be variable in their output, presumably determined by the availability of mass to provide gravitational energy.

The "statistical" lifetime of AGN, $\sim 10^{9}\, years$, 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 $10^{5}\, years$ [1,14,15].

Cosmic Ray Propagation Delays and Angular Deviations

The charged particles of CRs propagate through magnetic fields under the influence of the usual $q\vec{v} \times \vec{B}$ force in which we usually assume for simplicity that the charge q refers to the number of protons. In this case, a cosmic ray particle with energy of $10^{18} eV$ in a uniform magnetic field of strength $1 \mu G$ would have a gyration radius of $1 Kpc$, or $50 Mpc$ for a $50\, EeV$ proton in a nano-gauss field.

The magnetic fields with which we deal are believed to be dominated by turbulent structure [14] which has a characteristic scale to be found plus a form for the magnetic energy distribution over other scales (often assumed to be a of a Kolmogorov form). The result is that the propagation tends to a diffusive form which has the consequences of changing the propagation directions in random ways plus greatly increasing the time for a particle to reach a particular distance from its source. In simple diffusion, the time to reach a certain distance from the source increases with the square of the distance (as opposed to linear proportionality for conventional propagation) and it means that, for distances greater than a few scattering mean free paths, the process is very slow.

The detection of cosmic ray showers of above $60\, EeV$ [1, 2, 16], and knowing them of extragalactic origin [13, 17] made the highest energy cosmic rays a good probe to calculate the parameters of IGMF and

Table 1. Parameters of 27 Auger events [2]

Year	Julian day	θ	S(1000)	E(EeV)	RA	Dec	Longitude	Latitude
2004	125	47.7	252	70	267.1°	-11.4°	15.4°	8.4°
2004	142	59.2	212	84	199.7°	-34.9°	-50.8°	27.6°
2004	282	26.5	328	66	208.0°	-60.3°	-49.6°	1.7°
2004	339	44.7	316	83	268.5°	-61.0°	-27.7°	-17.0°
2004	343	23.4	323	63	224.5°	-44.2°	-34.4°	13.0°
2005	54	35.0	373	84	17.4°	-37.9°	-75.6°	-78.6°
2005	63	54.5	214	71	331.2°	-1.2°	58.8°	-42.4°
2005	81	17.2	308	58	199.1°	-48.6°	-52.8°	14.1°
2005	295	15.4	311	57	332.9°	-38.2°	4.2°	-54.9°
2005	306	40.1	248	59	315.3°	-0.3°	48.8°	-28.7°
2005	306	14.2	445	84	114.6°	-43.1°	-103.7°	-10.3°
2006	35	30.8	398	85	53.6°	-7.8°	-165.9°	-46.9°
2006	55	37.9	255	59	267.7°	-60.7°	-27.6°	-16.5°
2006	81	34.0	357	79	201.1°	-55.3°	-52.3°	7.3°
2006	185	59.1	211	83	350.0°	9.6°	88.8°	-47.1°
2006	296	54.0	208	69	52.8°	-4.5°	-170.6°	-45.7°
2006	299	26.0	344	69	200.9°	-45.3°	-51.2°	17.2°
2007	13	14.3	762	148	192.7°	-21.0°	-57.2°	41.8°
2007	51	39.2	247	58	331.7°	2.9°	63.5°	-40.2°
2007	69	30.4	332	70	200.2°	-43.4°	-51.4°	19.2°
2007	84	17.3	340	64	143.2°	-18.3°	-109.4°	23.8°
2007	145	23.9	392	78	47.7°	-12.8°	-163.8°	-54.4°
2007	186	44.8	248	64	219.3°	-53.8°	-41.7°	5.9°
2007	193	18.0	469	90	325.5°	-33.5°	12.1°	-49.0°
2007	221	35.3	318	71	212.7°	-3.3°	-21.8°	54.1°
2007	234	33.2	365	80	185.4°	-27.9°	-65.1°	34.5°
2007	235	42.6	276	69	105.9°	-22.9°	-125.2°	-7.7°

GMFs [18]. As they carry much less deflection in IGMF and GMFs, so it is possible that we understand their origin, nature and their propagation behavior from the source. Using a simulation model together with 27 Auger shower parameters (see Table 1), we calculated an average B and L_c for IGMF and GMF. Here we consider particles above $57\,EeV$ and in distances of less than $75\,Mpc$ of Auger showers which have not lost much of their energy through interaction with $2.7°K$ CMB (Greisen–Zatsepin–Kuzmin or GZK limit) [19, 20] and are correlated with nearby AGN [1, 2]. We consider their simulated propagation in the G, IG and Galaxy Cluster (GCL) magnetic fields. In this work especially looked at their propagation through a GMF extended to the halo. The deflection of UHECRs in GMF is important as it is needed to correct their arrival directions before they are compared with astrophysical sources. But indeed the deflection angles of UHECRs may provide information on magnetic field properties in their way from the source. For primary cosmic ray particles especially proton, the deflection in magnetic field is more important than its negligible loss.

Time Delay Calculation

A relativistic particle of charge qe and energy E in a magnetic field of strength B has a gyro-radius;

$$r_g = \frac{E}{qeB_\perp} \tag{1}$$

where $B_\perp$ is the field perpendicular to the particle momentum so the deflection angle:

$$\theta(E,d) = \frac{d}{r_g} \qquad (2)$$

where d is the distance from the source. If one describes τ as the time delay between stright line propagation of light from the source and traversing the deflected path (due to the magnetic field prependicular to the particle path) by a high energy particle (see Fig. 1) $R\theta_S$ *is equal to half of the arc* and for $D \ll R$, $X\ \theta_S$ *is equal to half of the cord*. It is continued with:

$$(\theta_S X)^2 = \theta_S{}^2\left(R^2 - D^2\right)$$

and:

$$\underbrace{\tau_{\frac{1}{2}}}_{\substack{\textit{time delay for traversing}\\ \textit{the half of the cord}}} = \frac{R\theta_S}{c} - \underbrace{\frac{\left(R^2-D^2\right)^{\frac{1}{2}}\theta_S}{c}}_{\substack{\searrow\\ \frac{R\theta_S}{c}\left(1-\frac{D^2}{2R^2}\right)}}$$

$$(i.e.\ for\ a\ high\ energy\ particle\ v \approx c)$$

So $\tau_{\frac{1}{2}} = \frac{D\theta_S{}^2}{2c},\ with\ \frac{D}{R} \sim \frac{D}{X} \approx \theta_S\ for\ D \ll R$ and using $\tau(E,d) = 2\tau_{\frac{1}{2}}$ one can represent the average time delay as

$$\tau(E,d) = d\,\frac{\theta^2(E,d)}{c} \qquad (3)$$

relative to the straight line propagation of light.

The magnetic field is often characterized by its strength B and correlation length L_c (i.e. B is smooth on scales below L_c). Considering formula (3) and also the three dimension random walk process

$$\begin{cases} \theta_S = \sqrt{3N}\,\dfrac{L_c}{r_g} \\ N = \dfrac{d}{L_c} \end{cases} \qquad (4)$$

with $\tau_E = \frac{\theta_S{}^2 d}{c}$ and $r_g = \frac{E}{qeB}$ it results to:

$$\tau_E = \frac{\left(\frac{3d}{L_c}\right)L_c{}^2}{r_g{}^2}\frac{d}{c} = 3\frac{q^2e^2B^2d^2L_c}{E^2c}$$

If d is comparable to or larger than the interaction length for stochastic energy loss due to photo-pion production or photodisintegration, the spread in deflection angles is always comparable to the average deflection angle (i.e. formula (1)) and the average time delay is given as follow [18, 21, 22, 23]:

$$\tau(E,d) \approx \frac{\theta^2(E,d)d}{4} \approx 1.5\times10^3 q^2 \left(\frac{E}{10^{20}eV}\right)^{-2}\left(\frac{d}{10Mpc}\right)^2\left(\frac{L_c}{1Mpc}\right)\left(\frac{B}{10^{-9}G}\right)^2 yr \qquad (5)$$

As a result, for each cosmic ray particle with E, d, q and τ or shower parameters of (E, θ, d); B^2L_c is a constant and it is a constraint which govern the behavior of a particle propagation. (see Fig. 2).

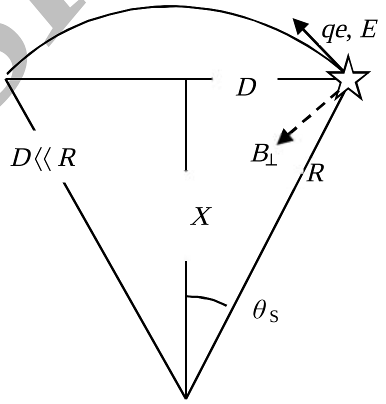

Figure 1. A relativistic particle with charge *qe* and energy *E* moving in a magnetic field of strength *B*.

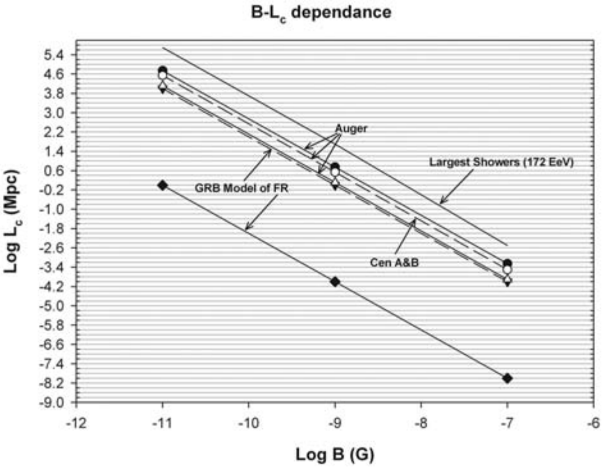

Figure 2. the Dependence of Intergalactic Magnetic field on its Galactic correlation length for the: observed Highest Energy Auger showers, its largest shower 172 EeV, Cen A&B Showers and FR&GRB Model; present simulation work.

So from the deflection and time delays of particles with different energies from their sources one could get information on B^2L_c (or equivalently $L_c^{\frac{1}{2}}$) or B and L_c from formula (5) [18]. But bearing in mind that protons and cosmic ray particles due to GZK cut off energy [19, 20] cannot come further away than about $100\,Mpc$, therefore in our case for distances of less than $75\,Mpc$, the particles should point back to their sources within a few degrees.

Results and Discussion

The Magnetic Fields

Considering Formula (5), one can see that the magnetic field affects the Time Delay and to know these effects in three regions of: the Galaxy, Extragalactic space, and the Galaxy Cluster we must use suitable approximation for each.

I Galactic Magnetic Field

There is conflicting predictions for UHECR deflection in GMF ranging from tens of degree [24] to less than a few degrees [25]. Considering the effect of Galactic *B* two methods were chosen:

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. [26], the central GMF strength is $6.4\,\mu G$ decaying exponentially to the larger Galactic distances. In this paper a spiral GMF been used which the size of deflection (in degrees) is given in Galactic coordinates (l,b) map. Having (l,b) of Auger showers, the deflection angles is obtained from galactic map and using formula (5) the time delays of events are calculated. The result of time delay distribution in GMF is shown in Figure 3, where its average value is $(57.67 \pm 76)\,years$ which is negligible compare to minimum time delays in IGMF (i. e. $3500\,years$). The consistency of Auger and simulated IGMF are also shown in the same figure for comparison. To calculate the effect of GMF on average $B^2L_c =$ $3.5\times10^{-18}\,G^2Mpc$ of observed Auger showers, we have chosen 3 particle energy of ranges $59, 70, 75\,EeV$ and calculated the time delays. The average changes on B^2L_c for the 3 energy ranges above were 14,108 and 9.3 percent respectively. 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 (see also [27]).

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 as $B = B_0 e^{\frac{-L}{3000}}$, where L is the disk height in Kpc and the regular magnetic field decays exponentially with a decay length $3000\,Kpc$ [28]. The gyroradius *R* of a particle with energy *E* in magnetic field *B* is $R(pc) = 1.08E(PeV)/B(\mu G)$. So for a given $x(b)$, the actual path of the charged particle is:

$$D(pc) = \int_0^{9000} \frac{3.77\times10^{-2}E}{B_0 e^{\frac{-L}{3000}}} \sin^{-1}\left\{\frac{B_0 e^{\frac{-L}{3000}} 9000}{2.16E\,\sin(b)}\right\} dL \qquad (6)$$

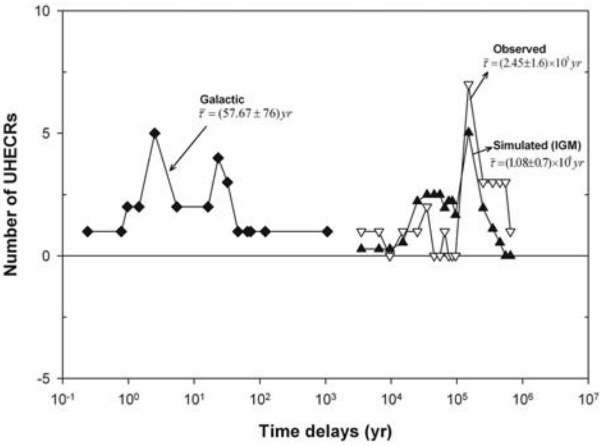

Figure 3. Distribution of the calculated Galactic time delay in comparison with the observed and simulated (IGMF) distribution of Auger Showers. It shows that the resulted events of the simulated program with the chosen parameters are close to the observed Auger Showers; present simulation work. $\bar{\tau} = (57.67 \pm 76)\,years$ for the simulated model used for GMF; $\bar{\tau} = (2.45 \pm 1.6)\times10^5\,years$ for the simulated model used for IGMF; $\bar{\tau} = (1.08 \pm 0.7)\times10^5\,years$ for the Observed Auger Showers.

and the time delay of each event is calculated as $\tau = 3.26\left(D - x\right) years$.

We calculated the time delay distribution of Auger showers for base Galactic magnetic field B_0 of $2,7,12\, and\ 20\,\mu G$. Magnetic field in the galaxy is estimated to be from $1\mu G$ to $1mG$ but more likely its maximum is above $10\,\mu G$ at the Galactic center [29]. Therefore for the above Galactic magnetic field B_0 the average time delays are obtained to be $\left(5+1.27\right)yr$, $\left(63.7+17.11\right)yr$, $\left(166.3+43\right)yr$ and $\left(522+159\right)yr$ respectively giving the minimum and maximum of particle time delays of $\left(B_0 = 2\mu G, b = -78.6\right)\tau =$ 0.13 years to $\left(B_0 = 20\mu G, b = 14\right)\tau =$ 3126 years which is less than minimum time delay in the case of IGMF of 3500 years. So it is negligible in comparison with a typical intergalactic and cluster time delays. Having time delay of each event in GMF, it is possible from formula (5) to calculate the value of $B^2 L_c$ for each shower where the effective Galactic *B* is;

$$B_{eff} = \left(\int_0^{9000} B_0 e^{\frac{-L}{3000}} \sin\left(b\right) dL\right) \Big/ \left(\int_0^{9000} \sin\left(b\right) dL\right) = 0.317 B_0 \tag{7}$$

Using the above B_{eff} make it possible that for a given B_0 to calculate L_c distribution, where the dependence of L_c (as its average and also its most probable value of L_c distribution) to B_0 is obtained and based on L_c distribution with less range of deviation, (i.e. $L_{c,\ Max} - L_{c,\ Min}$), which is consistence with B_0 values of 2 to $7\mu G$ and also emphasizes on the most probable L_c value, we concluded that the best values of B_0 and L_c are $B_0 = \left(5.25 + 3.25\right)\mu G$ which is consistence with the value of the previous work of a few micro-gauss increasing towards inner Galaxy (see [30]) and $L_c = \left(445 \begin{matrix} +341 \\ -105 \end{matrix}\right) pc$, in agreement with the result from FRM of halo of galaxies which gives GMF strength of $1\mu G$ and correlation length of $1Kpc$ [30].

Dividing the Auger data into center and anti center directions (i. e. $l < \left|0 - 90\right|$ and $l > \left|90 - 180\right|$ respectively) showed the higher L_c of $580\,pc$ in the direction of Galactic center to the value of $390.6\,pc$ in the anti center direction, reflecting higher B_0 towards center than anti center, a previous work also showed an increase of GMF towards the inner Galaxy [30]. So deflection in GMF depends on the arrival directions from center to anti center of the Galaxy (and of course on galactic $\left(l, b\right)$), therefore on the viewing area of a given experiment may show a different arrival direction of similar event. This point also mentioned by previous work for different located experiments [7].

II Intergalactic Magnetic Fields

The properties of IGMFs are poorly known. Magnetic fields in major clusters of galaxies have been measured to be high, with field strengths of a micro-gauss order have been reported [27]. On the other hand, definitive measurements of intergalactic medium between the clusters are almost non-existent. Strengths have been suggested as high as hundreds of nano-gauss [27] and as low as substantially below $10^{-11} G$ or less [28].

III Kolmogrov Type Magnetic Fields

Our simulation program has been performed assuming the cluster, intergalactic and galactic magnetic fields are in the form of Kolmogrov type with the turbulence energy spectrum of:

$$S\left(k\right) \sim k^{-\alpha} \begin{cases} for\ one\ dimention\ \alpha = \dfrac{5}{3} \\ k = wave\ number\ \dfrac{2\pi}{\lambda} \left(or\ \dfrac{2\pi}{L}, L\ is\ Eddy\ Size\right) \end{cases}$$

In such a field the square of the distance is proportional to the time path of particles, $d^2 = 2k_{\parallel} t$, where $k_{\parallel}$ is the diffusion coefficient along the line of sight. For the 27 Auger events the value of *k* found to be $0.006\,Mpc^2 yr^{-1}$, consistence with the Kolmogrov type spectrum.

IV Constraint on B and L_c

A practical method of measuring extragalactic magnetic fields is by Faraday Rotation Measure (FRM) of linearly polarized emission of radio sources given by [27]:

$$RM\ \left\{\Delta\chi / \left(\Delta\lambda^2\right)\right\} = 8.1 \times 10^5 \int n_e B_{\parallel} dl \quad \left(rad / m^2\right) \tag{8}$$

where χ is the rotation (degrees) of the plane of polarization measured at wavelength $\lambda(m)$, $n_e\left(cm^{-3}\right)$ is the local density of non relativistic electrons, $B_{\parallel}$ is the line of sight component of the field (G) and *l* is the path length (pc). Assuming the universe radius of $1.4\times10^{10}\,yrs \sim 5\times10^{9}\,pc$ for red shift of $z = 72$ and the upper limit of rotation measure of $2\,rad/m^2$, red shift of 3.6 [27], $n_e = 10^{-5}\,cm^{-3}$ and also knowing Hobble law, the distance for the upper limit of *RM* is calculated to be $250\,Mpc$, assuming Magnetic Cloud (MC) size of $1\,Mpc$, then the number of *MC*s are $N = 250$, and as *B* of the clouds are randomly directed, the effective *B* is $\sqrt{N}\,B$ and the upper limit of RM [27, 31, 32] from formula (8) is:

$$RM = 8.1\times10^{5}\times10^{-5}\int Bdl = 8.1\times2.5\times10^{8}B = 2$$

$$\Rightarrow\begin{cases} B = 10^{-9}G \\ L_c = 1Mpc \end{cases} \Rightarrow BL_c^{\frac{1}{2}} \leqq 10^{-9}\,GMpc^{\frac{1}{2}}$$

so the upper limit on IGMF from FRM is $BL_c^{\frac{1}{2}} \leqq 10^{-9}\,GMpc^{\frac{1}{2}}$. Also another constraint (rather than FRM) comes from baryon density [33] which gives a good estimate on IGMF correlation length of $10\,Kpc$ to $1\,Mpc$ and too high values of *B* range resulted as $B < \left(2\times10^{-7} - 6\times10^{-8}\right)G$ [33]. Two recent review about IGMF [34, 35] give a more reasonable upper limit of B_{IGMF} as $B < 10^{-9} - 10^{-8}G$ (without mentioning any estimates of range of correlation length of the field), so formula (5) is applicable assuming that the local large scale structure around the earth and also the super galactic plane is not strongly magnetized.

For the lower limit on $BL_c^{\frac{1}{2}}$, AGASA group [36], found three pairs of events and assumed that all events within a pair come from the same source. However the pair which contain $200\,EeV$ event seems to be significantly in favor of a comparatively small average time delay. They consider Gamma Ray Burst (GRB) model assuming the UHECRs and GRB have a common origin. The distance traveled by such particles must be smaller than $100\,Mpc$. Having GRB rate of $3\times10^{-8}\,Mpc^{-3}\,yr^{-1}$ [22] and assuming such a maximum distance likely to be traveled by a Cosmic Ray (CR) bigger than $7\times10^{19}eV$, CR rate is calculated to be one per 50 year [37]. So probability of the experiment to observe a CR pulse from a GRB event over a 10 year period is small unless the CR pulse is broaden in time due to the deflection by random *B* and energy dispersion of the particles [38]. If it is so and the time delay is much more than $50\,years$ then from formula (5), the lower limit on $BL_c^{\frac{1}{2}}$ is obtained to be $BL_c^{\frac{1}{2}} \geq 10^{-11}\,GMpc^{\frac{1}{2}}$ [37].

The above upper and lower limits on $BL_c^{\frac{1}{2}}$ used as constrains in our analysis.

Data Analysis

Applying the formula (5) and using the parameters of each shower, the quantity B^2L_c been calculated for each of them where its average value is obtained to be $B^2L_c = (3.5\pm2.4)\times10^{-18}\,Mpc\,G^2$ (We calculated a typical error on average $\hat{B}$ of 26 Auger showers $B = (4.2\pm1.9)10^{-9}G$ with care we reported $1-10\,nG$).

To more confirm this value the showers originated from Cen A and Cen B, two of the most powerful and cosmologically nearby correlated Auger sources of VHECRs [6], also been used separately. The result is in consistence with its value from all Auger showers, shown in Figure 2. Also in the figure, the $B^2 - L_c$ dependence is given for its lower and upper limits from GRB model and FRM respectively, the largest observed Auger shower (172 EeV) is also shown in the same figure for comparison. Now using the resulted constrains of time delays, range on B_{IGMF} as $\left(10^{-9} - 10^{-8}\right)G$ (see formula 5). With B^2L_c of the largest and all Auger showers and its upper limit, it is obtained that L_c should be larger than 0.53 and up to $1\,Mpc$. Living the value of B_{IGMF} to be $(2.22\pm1.11)\times10^{-9}G$ (the value of B^2L_c for the largest shower) and therefore its correlation length from the B^2L_c of all Auger Showers calculated to be $L_c = (467\pm160)\,Kpc$. Our value of IGMF is consistence with its ranged values estimated from FRM of $(1-10)\,nG$ [28], also with Stanev et al. [7] which gives consistence estimation of L_c up to $1\,Mpc$.

For the case of Galactic Cluster magnetic field and IGMF, the program options are strengths of *B* for the cluster and intergalactic space, their correlation lengths, the source distance, cluster size, particle energy and also regular and random field components in IGM and GCL regions. So for a set of the above inputs and also a similar case with $B_{IGMF} = 0$, we could get the extra path length of the particle relative to light and therefore its corresponding time delays. As an estimation of cluster size and its *B* strength we take use of recent work of Clark T. E., Kronberg P. P., and Böhringer H. [39]. They reported the result of RM on 16 galaxy clusters which shows RM excess out to $500Kpc$ from cluster center and at its edge, the magnetic field strength is about a few micro-gauss and increases towards cluster center. So in our simulation we assumed the same cluster size and magnetic field strength at the edge: $2\mu G$ increasing to $30\mu G$ at the central region of the cluster.

We assumed the source distance of $50Mpc$ and the particle energy of $70EeV$ (the average of Auger showers), $B_{IGMF} = 2nG$, $L_c = 0.48Mpc$ (based on our calculated results). The resulted average time delay of this simulation is about 10^7 *years* (even by inputting a much higher strength of $B_{GCL} = 0.5G$), shown in Figure 4. Our calculation showed that a typical Galaxy time delay is negligible as expected. AGN power also last about 10^7 *years* or longer [40] and being a continuous source. The correlation between Auger UHECR events and AGN result 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 [40].

Base on the observed time delays of UHECRs relative to the correlated local AGN and using the limits on $BL_c^{\frac{1}{2}}$ from FRM and GRB model, the simulated time delay distribution of UHECRs relative to light in G, IGM and GCL regions are calculated and presented. A typical time delay in G, IG and GCL magnetic fields is $10, 10^5$ and 10^7 *years*. Also an improved estimation of magnetic strength of G and IG fields and their correlation lengths are obtained to be [(5.25±3.25)μG, (445±31.17)pc] and [(2.22±1.11)nG, (476±160)Kpc], respectively. It is found that B_{GMF} towards the inner Galaxy is higher than anti center as expected. Our result is in the favor of bursting showers over a continuous cluster source. Our method with more observed showers of highest energy (with our patient for the time), would reconfirm the results and improve the statistical errors of the analysis.

Also we deduced: 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 $100Myr$, turbulent intergalactic magnetic fields with strengths above $100nG$ would seem to be excluded (Fig. 5).

Auger project cosmic ray arrival directions are correlated strongly with sources up to distances of $70Mpc$. For this to be true, or even if they are correlated with just 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 $100nG$ and probably below $20nG$ for most likely turbulence scales ($8, 16, 32Kpc$ shown in Figure 6). The result shows an upper limit closer to $10nG$ ($20nG$, if assumed that the sources must be within the supergalactic plane).

For a galaxy cluster we assumed cluster magnetic field of $2\mu G$ at the edge increasing to $30\mu G$ at the central region of the cluster. Also we assumed the source distance of $50Mpc$ and the particle energy of $70EeV$ (the average of Auger showers), $B_{IGMF} = 2nG$ (based on our calculated results). For such a magnetic field strength, comparing the simulation results with the data, suggests a best estimate of $\sim 500Kpc$ for the characteristic turbulence scale of the intercluster medium.

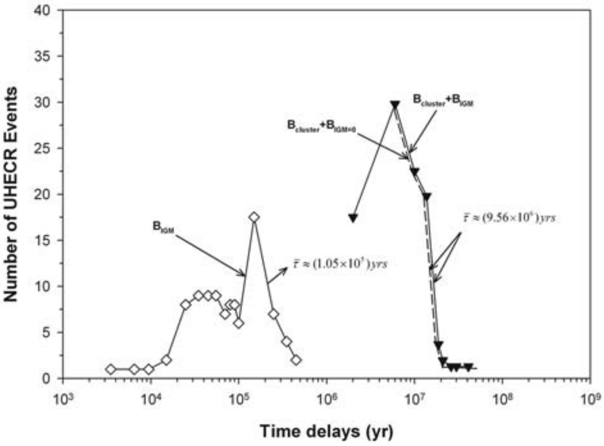

Figure 4. Right curve: the simulated time spread for a cluster source at distance of 50 Mpc, E=70 EeV, L_c=0.48 Mpc, $B_{cluster}$ =(30 to 2)μG and B_{IGM}=(2.15nG or zero) with $\bar{\tau} \approx 9.56 \times 10^6$ *years*. Left Curve: The time delay difference of the right curves. The time delay distribution is subtracted from it similar case but B_{IGM}=0 which results the time delay distribution for IGM plus our galaxy with $\bar{\tau} \approx 1.05 \times 10^5$ *years*. present simulation work. Conclusion: cosmic rays of 70 EeV spend 99% of their delayed propagation time (~ 10^7yrs) from cluster to the earth in the region of 500 Kpc from the cluster center.

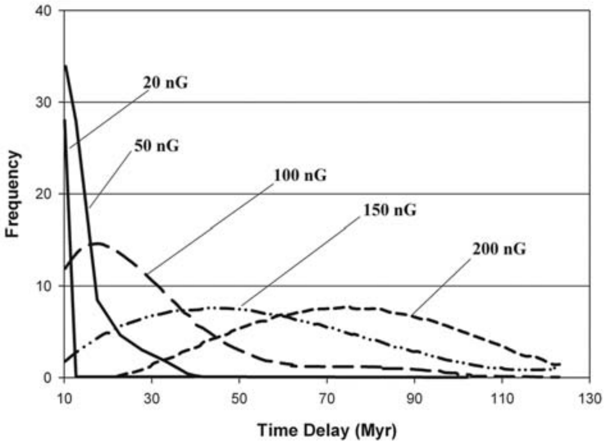

Figure 5. The simulated time delay distribution of Auger showers for various Intergalactic Field Strengths (16 Kpc turbulence scale, 50 Mpc total path length-typical source distance, and 50 EeV protons start propagation from randomly selected positions). It is seen that the number of detectable events reduces when the strength considered for IGMF increases; present simulation work. Conclusion: One of the inputs is the strength of B_{IGMF} which are given from 20nG to 200nG. so using an Auger shower of typical parameter for example (E=50EeV, d=50Mpc, L_c =16Kpc) for input of the higher $\hat{B}$ we would have higher time delays; Using formula 3 the calculated average time delays of Auger showers is of order $\sim 10^5$ years (0.1 Myr), so from Figure 5, $B < 20nG$ 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 5 concluded $\tau \leq 100\,Myr$ (life time of source) and $B \leq 100\,nG$, therefore $B > 100\,nG$ is excluded (which is correspond to τ larger than 100Myr).

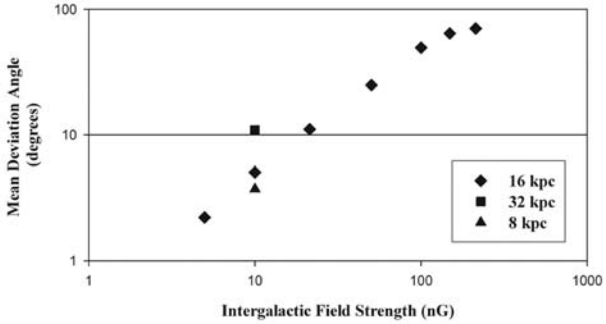

Figure 6. Propagation through a Turbulent Intergalactic Field (various turbulence scale lengths) for 50 EeV protons from a source at 50 Mpc. Conclusion: It is seen that for an about 10 nano-gauss IGMF (without a cluster field), the mean deviation is most when the turbulence scale considered to be 32 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; present simulation work.

Comparing the time delay simulation results for CRs above $70\,EeV$ in different cases of just IGMF, IGMF= 0 plus GCL and IGMF plus GCL it is showed that CRs with energies above $70\,EeV$ spend 99% of their delayed propagation time (10^7 $years$) from cluster to the Earth in the region of $500\,Kpc$ from cluster center (Fig. 4).

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