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INTERCLUSTER MAGNETIC FIELDS AND ULTRA HIGH ENERGY COSMIC RAYS

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SUMMARY: Cosmic rays 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 straight lines. Those delays can be so long that they are an impediment to correctly identifying sources, which may be variable in time. The magnitude of such delays will be discussed and compared to the characteristic time variation of possible cosmic ray sources.

Key words. cosmic rays – ISM: magnetic fields – Galaxies: general

1. INTRODUCTION

Cosmic rays are energetic charged particles which propagate to us through galactic and intergalactic magnetic fields. 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 AGN which are to be found within 75Mpc (The Pierre Auger Collaboration 2007).

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 (George et al. 2008) or that a better correlation may be with FR I/II radio galaxies with large jets (Nagar and Matulich 2008). That 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 3K CMB and lose energy with a characteristic distance of this order (the GZK effect).

It is also possible that the cosmic ray sources are not those specific AGN but that the sources simply follow the overall sky distribution of those AGN, the supergalactic plane (Stanev 2008). If we do assume that the cosmic rays are from the identified AGN, we can readily put limits on parameters of the galactic and intergalactic magnetic fields. Those limits correspond to a combination of the magnetic field strength and its characteristic turbulence scale.

2. INTERGALACTIC MAGNETIC FIELDS

The properties of intergalactic magnetic fields are poorly known. Magnetic fields in major clusters of galaxies have been measured to be high with field strengths of the order of microgauss (Kronberg 1994). On the other hand, definitive measurements of the intergalactic medium between the clusters are almost non-existent. Strengths have been suggested as high as hundreds of nanogauss (Kronberg 1994) and as low as substantially below a nanogauss. There are three regimes to be considered: fields extending out from our own galaxy into the 'halo', intracluster magnetic fields, and extra-cluster magnetic fields. Each of these is relevant in its way to cosmic ray studies and none is particularly well known.

3. COSMIC RAY SOURCES

Cosmic rays extend over a huge range of energies. At the lowest energies conventionally studied, cosmic rays 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 as 'ground level enhancements'. At higher energies (up to about 10^{14} eV particle energy) cosmic rays can be accelerated in supernova remnants through the mechanism of diffusive shock acceleration (Protheroe and Clay 2004). However, more recently, some researchers have analyzed the results based on the measurements of non-thermal emission from individual SNRs and their correspondence to the nonlinear kinetic theory of cosmic ray (CR) acceleration, and the outcome is a more efficient CR production and significant amplification of magnetic field, which leads to a considerable increase of cosmic ray's maximum energy. So, our galactic sources seem to be capable of accelerating particles to the energy above 10^{17} eV (Bell and Lucek 2001, Bell 2004, Berezhko 2008 and references therein), and it is usually assumed that higher energy particles are dominated by extra-galactic sources (Hillas 1984). At the highest energies, there is evidence for source directions being correlated with the supergalactic plane, so that those particles must be dominantly extragalactic in origin (The Pierre Auger Collaboration 2007).

The nature of the cosmic ray sources is not known at the highest energies but the 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 (Hillas 1984) 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 cosmic ray acceleration being through diffusive shock acceleration. This process is rather slow (Protheroe and Clay 2004) 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 the 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 the hard x-ray emission might be an indicator of candidate sources (George et al. 2008).

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 the gravitational energy.

The 'statistical' lifetime of AGN, 10^9 yrs, is estimated from the relative numbers of Seyfert and elliptical galaxies. The lifetimes of radio galaxies can be estimated from dynamical processes, comparing their sizes and expansion rates. For low and high power radio galaxies, these 'dynamical' ages are in the ranges 10^{7-8} and 10^{6-7} years respectively. Seyfert galaxies have dynamical ages which are shorter than this and are estimated to be on or below the order of 10^5 years. Seyferts were the predominant AGN which are correlated with ultra high energy cosmic rays in the original (The Pierre Auger Collaboration 2007) Auger result (Sanders 1984, Ho et al. 1997).

5. COSMIC RAY PROPAGATION DELAYS AND ANGULAR DEVIATIONS

Cosmic rays are charged particles and they propagate through magnetic fields under the influence of the usual qvB force in which we usually assume, for simplicity, that the charge q refers to protons. In this case, a cosmic ray particle with an energy of 10^{18} eV in a uniform magnetic field of strength 1 microgauss would have a radius of gyration of 1 kpc, or a 50 Mpc for a 50 EeV proton in a nanogauss field.

The magnetic fields we deal with are believed to be dominated by a turbulent structure (Sanders 1984) which has a characteristic scale to be found as well as a form for the magnetic energy distribution over other scales (often assumed to be of a Kolmogorov form). The result is that the propagation tends to a diffusive form and this has the consequence of changing 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 the linear proportionality for conventional propagation) which means that, for distances greater than a few scattering mean free paths, the process is very slow.

In this work, assuming Kolmogrove type spectrum for the cluster, intergalactic and galactic magnetic field strength, the average time delay and the average deviation angles of high energy cosmic rays are simulated. The program options are magnetic field strength for cluster and intergalactic space, their correlation lengths Lc, the source distance d, cluster size, and particle energy. Regular and random field components in intergalactic magnetic field (IGM) and galactic clusters (GCL) regions, as well as the azimuth and zenith angles are also assumed. For estimation of cluster size and its B strength, we make use of the work of Clark et al. (2001). In this simulation, a cosmic ray particle with energy E starts to travel through the galactic clusters (GCL). The particle moves randomly with the speed near that of light. When the traveling distance is equal to the source distance d (i.e. 50 Mpc) the program is stopped. For a set of above inputs and also in a similar case but with $B_{\mathrm{IGM}} = 0$, we could get the extra path length of the particle relative to the light and, therefore, its corresponding time delays for fixed E, B and the source distance d. Because of the particle random motion, even with the same inputs, we get different time delays. As the simulation has been running for the specified number of showers N, we have a distribution of time delays (Fig. 1).

Auger project cosmic rays have been correlated with AGN directions up to 75 Mpc. For the sources to really be AGN and there to be a strong correlation, the delay behind directly propagating light incurred by the cosmic rays must be much less than the lifetime of the sources. With a likely upper limit source lifetimes of the order of 100 Myr, turbulent intergalactic magnetic fields with strengths above 100 nG would seem to be excluded (Fig. 1).

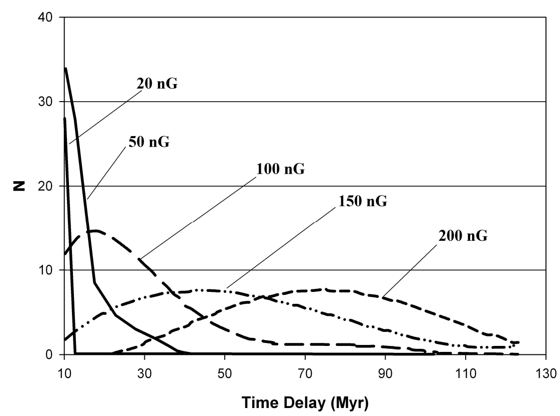

Fig. 1. *Time Delay for Various Intergalactic Field Strengths (16 kpc turbulence scale, 50 Mpc total path length, 50 EeV protons), (N is the number of simulated showers).*

Auger project cosmic ray arrival directions are correlated strongly with sources up to distances of 75 Mpc. For this to be so, or even if they are correlated with just the supergalactic plane, total directional deviations must be less than 10° (or much less than for point sources). This limits the average intergalactic field strength to below 100 nG and probably below 20 nG for most comparable turbulence scales (8, 16, 32 kpc shown) (Fig. 2).

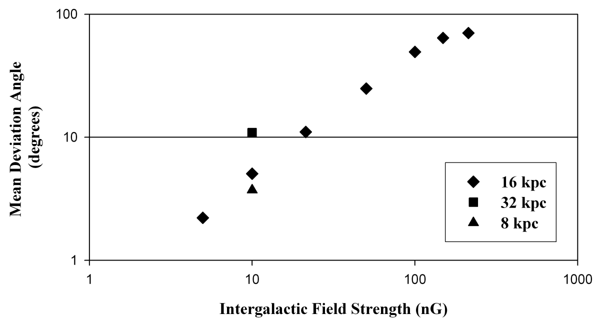

Fig. 2. *Propagation through a Turbulent Intergalactic Field (various scale lengths) for 50 EeV protons from a source at 50 Mpc.*

6. ANGULAR DEVIATIONS OF AUGER DIRECTIONS

Cosmic rays diffusing through a turbulent magnetic medium are deflected in such a way that their angular deviation depends on the magnetic field strength (B) and its correlation length L_c (defined as the field characteristic turbulence scale or the scale bellow which the B - field is smooth). The average time delay implies an average deviation angle (see Sigl et al. 2004) since time delay is proportional to B^2L_c (Sigl et al. 2004), A larger B reflects a longer time delay and also more deviation for cosmic ray particles which is concluded from Fig. 2.

The Pierre Auger Observatory (The Pierre Auger Collaboration 2007) found a correlation between the arrival directions of its 27 highest energy events and the directions of the closest AGN (within 75 Mpc). Using these combinations of directions for 26 of these events, and independently for the highest energy event, we are able to place constraints on the B^2L_c parameter. If we assume that a typical value for the magnitude of B in inter-cluster space is in the range 1-10 nG, we find that a reasonable combination of values is a B-field of a few nanoGauss with the correlation length for the magnetic field (L_c) of the order of 500 kpc.

7. CONCLUSION

We have presented the results of cosmic ray propagation calculations to understand the implications of recent results from the Pierre Auger Observatory which demonstrate a correlation between the arrival directions of cosmic rays with energies above 50 EeV and the directions of AGN up to distances of 75 Mpc. AGN have a limited lifetime and this limits the acceptable delay behind the light travel time for cosmic rays diffusing through the intergalactic magnetic field. Also, the directional correlation between the cosmic rays and AGN positions limits the acceptable scattering angles for the propagating cosmic rays. Our propagation calculations show that both of these constraints set the upper limits of 100 nG on the mean magnetic field strength of the intercluster medium with the directional constraint probably being the stronger, giving the upper limit closer to 10 nG (20 nG if the assumption is only that the sources must be within the supergalactic plane). For such a magnetic field strength, the data suggest a best estimate of 500 kpc for the characteristic turbulence scale of the intercluster medium.

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МЕЂУГАЛАКТИЧКО МАГНЕТНО ПОЉЕ И УЛТРА ВИСОКО-ЕНЕРГЕТСКО КОСМИЧКО ЗРАЧЕЊЕ

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Оригинални научни рад

Космички зраци се крећу брзинама које су јако блиске брзини светлости. Ипак, док путују кроз магнетно поље, хомогено и турбулентно, они касне за светлошћу због тога што су наелектрисане честице и као резултат интеракције са магнетним пољем путање им нису праве линије. Ова кашњења могу бити толико велика да не омогућују коректно идентификовање извора који могу да буду променљивог сјаја током времена. Временска трајања оваквих кашњења ће бити продискутована и упоређена са карактеристичним временима променљивости могућих извора космичког зрачења.