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NON-DIFFUSIVE PROPAGATION OF ULTRA HIGH ENERGY COSMIC RAYS

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Abstract

We report the results of 3-D simulations of non-diffusive propagation of Ultra-High Energy Cosmic Rays (UHECR) ($E > 10^{20}\, eV$) through the intergalactic and extended halo media. We quantify the expected angular and temporal correlations between the events and the sources, and the temporal delay between protons and gamma-ray counterparts with a common origin for both halo and extragalactic origins. It is shown that the proposed UHECR-supergalactic plane source associations require either extremely high values of the halo magnetic field over as much as 100 kpc length scale or a very large correlation length for the IGM, even for the largest possible values of the intergalactic magnetic field. It can be stated that the UHECR seem to point to the sources even more strongly than previously believed. The simulations also show that the calculated time delays between UHE protons and gamma-ray counterparts do not match the claimed GRB-UHECR associations for either cosmological or extended halo distance scales.

1. Introduction

The recent detection of several UHECR beyond 100 EeV ($1\,EeV = 10^{18}\,eV$) poses a challenge for the understanding of their sources. First, the extreme energies are difficult to obtain from *any* astrophysical source [1]. Second, because of photomeson production due to interactions with the CMBR photons, protons loose substantial amounts of energy $\Delta E/E \sim 10 - 20\%$ per collision along their path to the Earth, leading to a theoretical cutoff of the primary spectrum at $E_{max} \simeq 5 \times 10^{19}\,eV$ (Greisen-Zatsepin-Kuzmin or GZK cutoff) in the case of an extragalactic origin.

Possible acceleration mechanisms require either direct accelerators (high magnetic fields and rotation rates to produce a large induced e.m.f. or reconnect the field lines) or statistical accelerators (powerful shocks), each one with their own difficulties for reaching UHE [1,2,3]. In principle both galactic and extragalactic environments are allowed. Several sites have been put forward to explain the origin of these UHECR.

Specific candidates include magnetars (pulsars with anomalously large magnetic fields $B \geq 10^{14}\,G$) as the most likely galactic source [4]. This possibility is particularly interesting because magnetars are invoked as the sources of Soft-Gamma Repeaters (SGR), now firmly identified with young SN remnants [5]. If a rotating magnetar has a surface field B, a radius R, and a rotational frequency Ω, a circuit connected between the pole and the last open field line would see an e.m.f $\sim \Omega^2 B R^3 c$. The corresponding maximum energy that a particle can extract from the rotating magnetar is then

$$E_{max} \sim 1.7 \times 10^{21} \left(\frac{\Omega}{10^4\,s^{-1}}\right)^2 \left(\frac{B}{10^{14}\,G}\right) \left(\frac{R}{10\,km}\right)^3 eV \qquad (1)$$

for direct acceleration along open field lines [1,6,7].

A magnetar may also provide UHECR through particle acceleration in reconnection regions. If we assume that magnetic loops expand by Parker instability [8,9] on the surface, a one-dimensional analysis of the reconnection shows that the maximum kinetic energy that a particle (e.g., proton) can extract from the reconnection region is

$$E_{max} \simeq 2.2 \times 10^{20} \left(\frac{n}{10^8 cm^{-3}} \right)^{-1} \left(\frac{B}{10^{14} G} \right) eV \qquad (2)$$

where n is the particle density at the magnetosphere. Another version of (coherent) large-scale acceleration has been advocated by Colgate [10] as an alternative powerful mechanism that may be operative in the halo.

At even larger distance scales FR II radio sources and AGNs have been also considered [11,12] because they are known to be energetic and accelerate at least e^- to form jets, although the efficiency for UHE acceleration (through stochastic processes) is quite uncertain, and the GZK cutoff certainly applies to them. Other cosmological sources for the UHECR have been studied by Bird el al. [13] , Yoshida et al.[14], Waxman [15] and Milgrom and Usov [7]. Finally, models in which topological defects accelerate the primaries may be involved. For example, Sivaram [16] argues that a single cosmic string may match the UHECR energy and flux requirements, producing up to $10^{22}\, eV$ protons. In this sense, the detection of UHECR will serve to boost the theoretical study of topological defect dynamics, sites that can not be completely excluded at present and remain an interesting possibility.

An even more urgent question than the details of the process capable of accelerating

the UHECR is the distance scale to the sources and the angular correlation of the events with them; i.e., another version of the galactic vs. extragalactic debate. Arguments for the association of UHECR with extragalactic sources have been presented by Rachen and Biermann [17], Biermann [11] and Stanev et al. [18], who contend that the events exhibit a correlation with the supergalactic plane. Wydoczyk and Wolfendale [19] have discussed the features of a Giant Halo Model acceleration scenario, while Waxman [15] and Vietri [20] , and Vietri [21] have discussed the energy budget and observational constraints for a cosmological and coronal origin respectively. Furthermore, Milgrom and Usov [7,22] have claimed a positional association with gamma-ray bursts preceding the two highest-energy UHECR by 5.5 and 11 months respectively, and a related discussion on this important point has been given by Vietri [21] . We must not forget that even the very nature of the primaries is hotly debated. Neutrinos and gammas, for example, can not be completely discarded (see however [23]), although the simplest hypothesis of protons being the primaries is reasonable and will be adopted throughout this work.

With the aim of helping to elucidate the problem of UHECR source identification we perform in this work 3-D simulations of individual proton trajectories propagated through the IGM, halo and ISM components. We calculate the angle α between the arrival direction and the line-of-sight to the source and the time delay $\Delta\tau$ of the UHECR with respect to photons. The next sections describe the numerical simulations performed to address these points and present the results for the use of model builders.

2. Simulations

To study the quantitative features of UHECR propagation in the ISM, halo and IGM

we have performed 3-D numerical simulations of the trajectories of the energetic particles in the intergalactic and interstellar magnetic fields, including the relevant losses due to their interaction with the CMBR photons. As a reasonable working hypothesis we assume that the magnetic field inside the propagation region is uniform on scales smaller than its correlation length L_c [11,24]. The 3-D space is divided in domains randomly generated out of a normal distribution of average length-scale L_c and 10 % standard deviation. The magnetic field is assumed to be homogeneous inside each domain and randomly oriented with respect to the field in adjacent domains (c.f. [11]). Particles are injected into the system at different energies and pitch angles with respect to the line of sight θ. Our aim is to follow explicitely the 3-D trajectories of the protons through the magnetized media. We note that, although the path of the particles is expected to be a random walk in most aspects (and thus somewhat predictable by simple arguments), only 3-D numerical calculations will allow an accurate explicit determination of α and $\Delta\tau$, an information which is necessarily lost in diffusion-type schemes [3,24,25]. In this way we avoid to make a dangerous extrapolation of the diffusion coefficients to the highest energies.

Since we are interested in the UHE regime alone, we have only considered the dominant loss mechanism of photomeson production [24,26-28], neglecting e^+e^- production due to its very small inelasticity for $E \geq 10^{20}\, eV$. To model this process we use the characteristic collision time between a proton of energy $E \gg m_p c^2$ and a photon at the CMBR equilibrium temperature $T = 3\, K$ calculated by [10]. We considered that in each collision the energy loss $\Delta E/E$ increases linearly from 0.13, at $E = 10^{20}\, eV$, to 0.22, at $2.3 \times 10^{20}\, eV$ at the $(3/2, 3/2)$ resonance [27], being constant at higher energies (this sets

a *lower* limit estimate to the actual losses due to the onset of multiple pion production). The output parameters of the simulation are the time of flight between the injection site (the source) and the detector τ, the arrival energy E and deviation angle α from the line of sight for each propagated particle.

Several numerical experiments have been performed by injecting $\sim 8 \times 10^5$ particles having a $N(E) \propto E^{-2}$ spectrum in the energy interval $2 \times 10^{19}\, eV - 1 \times 10^{23}\, eV$, except in the calculations leading to Fig. 1 where we have injected monochromatic spectra ranging from $10^{21} eV$ to $10^{23} eV$. Although the propagated particles are tracked down to energies bellow $10^{20} eV$, our analysis will focuse on $E > 10^{20} eV$. The simulations were performed for sources of UHECR at galactic ($10\, kpc$), extended halo ($100\, kpc$) and nearby extragalactic ($50\, Mpc$) distance scales (different propagation models and physical conditions will be presented elsewhere [29]).

Motivated by the recently proposed associations of UHECR with some extragalactic sources [18] and a possible GRB-UHECR connection [7] we mainly discuss the results of the extended halo and extragalactic cases. The results of those simulations can be appreciated in Figs.1-5, which depict the observable quantities we are interested in (see captions for details). All the presented data neglects the very small deflection of the local (disk) ISM which does not contribute appreciably to the total α. We discuss the meaning of these results in the next Section.

3. Results and Discussion

From the results presented in Fig. 1, and in agreement with the GZK cutoff expectation, our work also shows that an extragalactic origin is possible if $d \leq 50\, Mpc$, otherwise the

injection energy must be unreasonably high. This is in good agreement with previous diffusion-type calculations (e.g. [3,23,24,28]) and serves as a check of the code against those works mostly interested in the energy distribution of the arrival particles.

Let us discuss first the case of extended halo sources [7,10,21]. Fig. 2a shows the arrival angle α as a function of the energy E for a source located inside a maximally magnetized ($B_H = 10^{-6}\,G$) extended halo at a distance $d = 100\,kpc$. As expected, this dependence is quite strong. However, in the energy regime we are interested in α varies from $\sim 10^o$ to $\sim 6^o$ for the highest energy observed events. Therefore, in the hypothesis of a common halo origin of GRB and UHECR, the error circles that can be determined for the latter are *less* restrictive than those of GRB, making any individual positional association very uncertain. Furthermore, given the low value of the UHECR flux $\sim 5 \times 10^{-12}\,erg\,cm^{-2}\,s^{-1}\,sr^{-1}$ it seems impossible to collect enough events for any other statistical positional correlation with known halo objects to make sense. We have checked that these results are robust with respect to variations in B_H and L_c as long as $10^{-9}\,G < B_H > 10^{-6}\,G$ and $Lc < 3\,kpc$.

As first stressed by Migrom and Usov [7] and other authors, the existence of a *temporal* correlation between GRB and UHECR would be very important to understand the location and physics of the sources. To investigate this point we have plotted in Fig. 2b the probability density distribution $P(\Delta\tau)$ of the arrival time delay $\Delta\tau$ between a photon and a UHE proton originated at the same event. Our explicit following of the trajectories shows that a considerable temporal spread is present and the expected value of $\Delta\tau$ peaks at $\sim 10^3\,yr$. A delay $\leq 10\,yr$ has a probability of $\leq few \times 10^{-4}$ for protons

of $10^{20}\,eV < E < 3 \times 10^{20}\,eV$. This means that if we assume a common GRB-UHECR source with $\sim 1\,yr$ delay, the total energy in UHE protons of the the event should be $\sim 10^{57}\,erg$ for isotropic emission. The numbers quantify the brief discussion given in [7] and show that the association hypothesis faces severe problems for this distance scale. Needless to say, the problems of having a temporal correlation as short as $\sim 1\,yr$ are worse for the other currently favored GRB distance scale, namely a cosmological one which we do not address. The result is again not sensitive to changes in B_H and L_c within the previously given range. Moreover, the combined results suggest that a correlation between GRBs and lower energy protons ($10^{19}\,eV$ energy bump is even weaker (see for example [30] for a recent search).

We turn now to the extragalactic case. The basic features of an extragalactic source injecting protons at $d = 50\,Mpc$ are shown in Figs. 3-5 (see captions for details). We begin discussing the influence of the IGM alone and later include the combined effect of a halo for different assumptions. Let us consider first $B_{IGM} = 10^{-9}\,G$ and $L_c = 1Mpc$, hereafter denoted as the fiducial case (see [31]). From Fig.3 (lower curve) it can be appreciated that the IGM by itself is not enough to produce considerable deflection for protons of $E \geq 10^{20}\,eV$. Therefore, within an error circle of at most 8^o, the particles point to their sources. These error circles reduce to a mere 2^o for the highest energy detected event. Thus, taken at face value, an association with sources lying in the supergalactic plane [18] seems to be unlikely (although the pair of Yakutsk-Fly's Eye events could come from a single source). At least two assumptions (capable in principle of changing this conclusion) deserve further analysis. The first one is the value of B_{IGM} which, even if it is considered

a reasonable upper limit [31], is extracted from rotation measurements that involve L_c and hence depends on it. B_{IGM} is known to scale approximately as $L_c^{-1/2}$. Fig. 4 shows the effect of varying L_c over a wide range on the arrival angle α of UHECRs. Due to energetic arguments on B_{IGM}, any other reasonable normalization allowed by the observational data will produce α values lying *below* the one in Fig. 4 and thus this curve could be considered as an upper limit. It seems that the deviation angle can not be increased by altering either B_{IGM} for a given L_c or L_c for a given (*smaller*) B_{IGM}. The second major modification is the obvious inclusion of a halo. To maximize the deviation due to this component we have repeated the calculations including an extended ($R_H = 100\,kpc$), strongly magnetized halo ($B_H = 10^{-6}\,G$; $L_c = 1.5\,kpc$) [30], which is shown in the upper curve of Fig.3. In this case a source located in the supergalactic plane can not be excluded. We emphasize, however, that this is a rather extreme case, as can be checked from the curves presented in Fig. 5. It is seen that the deflecting power of the halo on extragalactic incoming particles quickly decays with its magnetic field B_H and size R_H (lower curve). If B_H happens to be $0.2\,\mu G$ as some observations suggest, then the halo plays almost no role at all and the deflection angle is entirely due to the IGM presence ($\sim 5^o$ in the particular case of our fiducial IGM case, Fig.5). The situation does not change appreciably in either case by, for example, doubling the halo correlation length (indicated by the three simulations represented by the symbols, see caption).

In summary we have presented a set of numerical models devised to keep the basic features for the propagation of protons through IGM and extended halo concerning the combined deviation and time delay. From the analysis of the results we have argued

that, even if not ruled out, an association of UHECR ($E > 10^{20} eV$) with either GRB or supergalactic plane sources require rather strong assumptions on the size of the halo and/or the correlation length of B_{IGM}. It is apparent that more work on these subjects is needed to elucidate the final origin of UHECR. Note that at energies lower than $10^{20} eV$, other particle interactions besides those considered in the present work could be relevant and so our conclusions should not be extrapolated to that energy range.

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Figure captions

Figure 1. Arrival energy of UHE protons E as a function of the distance to the source d for several values of the (monochromatic) injection energy $E_{\mathbf{inj}}$.

Figure 2. a) Arrival angle α of a proton of energy E. Extended halo case for a power-law injected spectrum (see text),source distance $d = 100\,kpc$, magnetic field strength $B_H = 10^{-6}\,G$ and $L_c = 1.5\,kpc$. 2 b) Probability density distribution $P(\Delta\tau)$ as a function of the proton delay with respect to photons $\Delta\tau$, assuming simultaneous injection at the source. The error bars reflect the resolution of the simulations.

Figure 3. The same as in Fig. 2a for an extragalactic source at $d = 50\,Mpc$. The curves are given for $B_{IGM} = 10^{-9}\,G$, $L_c = 1\,Mpc$ without considering the effects of B_H (lower curve) and, for the same values of the IGM, with the inclusion of a maximally magnetized halo having $B_H = 10^{-6}\,G$, $L_c = 1.5\,kpc$ and size $R_H = 100\,kpc$ (upper curve). See the discussion in the text.

Figure 4. Upper limit to the arrival angle α as a function of L_c allowed to increase from the normalization point value $B_{IGM}(L_c = 1\,Mpc) = 10^{-9}\,G$. Values of $L_c < 1\,Mpc$ would require even higher B_{IGM} and begin to violate energetic constraints.

Figure 5. Influence of the halo on the arrival angle of extragalactic protons injected at $d = 50\,Mpc$ with a power-law spectrum and traveling through an IGM having $B_H = 10^{-6}\,G$ ordered on $1\,Mpc$ scale. Two different halo models are considered : a conservative one of a characteristic size R_H of $10\,kpc$ (lower curve) and an extended one with $R_H = 100\,kpc$ (upper curve). The curves span all cases ranging from asymptotically negligible halos (for $B_H < 10^{-7}\,G$) to maximally deviating halos having $B_H = 10^{-6}\,G$

(end of the curves). (the observations actually suggest a value of about $0.2\,\mu G$, see [31]) The curves have been calculated assuming a halo $L_c = 1.5\,kpc$. The symbols show three simulations in which L_c has been doubled for $R_H = 10\,kpc$ (crossed circles) and $R_H = 100\,kpc$ (square), showing the insensitivity of the results to this parameter.

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