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IMPLICATIONS OF A POSSIBLE CLUSTERING OF HIGHEST ENERGY COSMIC RAYS

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ABSTRACT

Very recently, a possible clustering of a subset of observed ultrahigh energy cosmic rays above $\simeq 40\,\mathrm{EeV}$ ($4 \times 10^{19}\,\mathrm{eV}$) in pairs near the supergalactic plane was reported. We show that a confirmation of this effect would provide information on origin and nature of these events and, in case of charged primaries, imply interesting constraints on the extragalactic magnetic field. The observed time correlation would most likely rule out an association of these events with cosmological gamma ray bursts. If no prominent astrophysical source candidates such as powerful radiogalaxies can be found, the existence of a mechanism involving new fundamental physics would be favored.

Subject headings: cosmic rays – gamma rays: theory – magnetic fields

1. Introduction

The recent detection of ultrahigh energy cosmic rays (UHE CRs) with energies above 100 EeV (Bird et al. 1993, 1994, 1995a; Hayashida et al. 1994; Yoshida et al. 1995) has triggered considerable discussion in the literature on the nature and origin of these particles (Sigl, Schramm, & Bhattacharjee 1994; Elbert & Sommers 1995; Halzen et al. 1995). On the one hand, even the most powerful astrophysical objects such as radio galaxies and active galactic nuclei (AGN) are barely able to accelerate charged particles to such energies (Hillas 1984). On the other hand, above $\simeq 70$ EeV the range of nucleons is limited by photopion production on the cosmic microwave background (CMB) to about 30 Mpc (Greisen 1966; Zatsepin & Kuzmin 1966), whereas heavy nuclei are photodisintegrated on an even shorter distance scale (Puget, Stecker, & Bredekamp 1976). In addition, protons above 100 EeV are deflected by only a few degrees over these distances, if one uses commonly assumed values for the parameters characterizing the galactic and extragalactic magnetic fields (Sigl, Schramm, & Bhattacharjee 1994).

Currently there exist three classes of models for UHE CRs. The most conventional one assumes first order Fermi acceleration of protons at astrophysical magnetized shocks (see, e.g. Blandford & Eichler 1987). This mechanism is supposed to be associated with prominent astrophysical objects such as AGN and radio galaxies. One problem with this scenario is that no obvious candidate could be found within a cone around the arrival direction of the two highest energy events observed whose opening angle is given by the expected proton deflection angle (Elbert & Sommers 1995; Hayashida et al. 1994).

Recently a second class of models has been suggested; namely that UHE CR could be associated with cosmological gamma ray bursts (GRBs) (Waxman 1995a,b; Vietri 1995a; Milgrom & Usov 1995). This was mainly motivated by the fact that the required average rate of energy release in γ-rays and UHE CRs above 10 EeV turns out to be comparable. Protons could be accelerated beyond 100 EeV within the relativistic shocks associated with fire ball models of cosmological GRBs (Meszaros 1995). One advantage of such a scenario is that sources are not necessarily correlated with powerful astrophysical objects. In fact, the high degree of isotropy observed in the GRB distribution (see, e.g., Fishman & Meegan 1995) would, apart from magnetic deflection of the protons, predict a highly isotropic UHE CR distribution as well. Since the rate of cosmological GRBs within the field of view of the cosmic ray experiments which detected events above 100 EeV is about 1 per 50 yr, a dispersion in UHE CR arrival time of at least 50 yr is necessary to reconcile observed UHE CR and GRB rates. Such a dispersion could be caused by the time delay of protons due to magnetic deflection (Waxman 1995a, Waxman & Coppi 1996).

The third class of models are the so-called "top-down" (TD) models. There, particles are created at UHEs in the first place by the decay of some supermassive elementary "X" particle associated with possible new fundamental particle physics near the grand unification scale (Bhattacharjee, Hill, & Schramm 1992). Such theories predict phase transitions in the early universe which are expected to create topological defects such as cosmic strings, domain walls and magnetic monopoles. Although such defects are topologically stable and would be present up to today, they could release X particles due to physical processes such as collapse or annihilation. Among the decay products of the X particle are jets of hadrons. Most of the hadrons in a jet (of the order of $10^4 - 10^5$) are in the form of pions which subsequently decay into γ-rays, electrons, and neutrinos. Only a few percent of the hadrons are expected to be nucleons (Hill 1983). Typical features of these scenarios are thus the predominant release of γ-rays and neutrinos and spectra which are considerably harder than in case of shock acceleration. For more details about these models, see, e.g. Bhattacharjee & Sigl 1995.

Most recently, a possible correlation of a subset of events above 40 EeV among each other and with the supergalactic plane was reported by the AGASA experiment (Hayashida et al. 1996). Among 20 events with energy above 50 EeV, two pairs with an angular separation of the paired events of less than $2.5°$ were observed within $10°$ of the supergalactic plane. The probability for that to happen by chance for an isotropic, unclustered distribution was given to be $\simeq 6 \times 10^{-4}$. A third pair was observed among 36 showers above 40 EeV, with a chance probability of about 1% (Hayashida et al. 1996). This suggests that the events within one pair have been emitted by a single discrete source possibly associated with the large scale structure and within a time scale of order 2 yr or shorter. The fact that the lower energy events in the pairs observed by AGASA always (albeit with very poor statistics since only 3 pairs were observed) arrived later suggests that the pair was produced in a burst and the time delay is dominated by magnetic deflection of the (charged) lower energy particle. Furthermore, the distance to the source cannot be much larger than $\simeq 30$ Mpc if the higher energy event has been caused by either a nucleon, a nucleus, or a γ-ray, since its energy was observed to be $\gtrsim 75$ EeV in all three pairs.

In this Letter we investigate possible consequences of a confirmation of the above mentioned scenario of bursting sources suggested by the AGASA results. In §2 we discuss consequences for the strength and structure of the galactic and extragalactic magnetic fields. In §3, implications for the different classes of UHE CR models currently discussed in the literature are addressed. We summarize our findings in §4. Throughout the paper we use natural units with $c = \hbar = 1$.

2. Magnetic Field Constraints from Time Delay and Deflection

Let us assume that the extragalactic magnetic field (EGMF) can be characterized by a typical field strength B and a coherence length scale l_c. Over distances $r < l_c$, a relativistic particle of energy E and charge e will then be deflected by an angle $\alpha = r/r_l$ where $r_l = E/eB$ is the Larmor radius. Assuming a random walk over distances $r > l_c$ leads to an average deflection angle $\alpha_{\rm rms} = (r/l_c)^{1/2} l_c/r_l$. The time delay τ caused by these deflections can then be written as

$$\tau \simeq \frac{\alpha_{\rm rms}^2 r}{2} = 9 \times 10^3 \left(\frac{E}{100\,{\rm EeV}}\right)^{-2} \left(\frac{r}{10\,{\rm Mpc}}\right)^2 \left(\frac{B}{10^{-9}\,{\rm G}}\right)^2 \left(\frac{l_c}{1\,{\rm Mpc}}\right) {\rm yr}\,. \tag{1}$$

Assuming that the correlated events have been produced in a burst on a time scale much shorter than 1 yr such that the time delay $\simeq 2$ yr observed by AGASA is dominated by the deflection time Eq. (1) for the lower energy event with energy $E \simeq 50$ EeV, the first equality in Eq. (1) implies

$$\alpha_{\rm rms} \simeq 0.012^\circ \left(\frac{r}{30\,{\rm Mpc}}\right)^{-1/2} . \tag{2}$$

Thus, if the observed angular deviation of the correlated events of about 2° is caused by deflection and not by the finite angular resolution (which is $\simeq 1.6^\circ$), the contribution of the EGMF to the deflection must be negligible. From this we obtain the following constraint on the EGMF:

$$B \lesssim 2.5 \times 10^{-12} \left(\frac{l_c}{1\,{\rm Mpc}}\right)^{-1/2} \left(\frac{r}{30\,{\rm Mpc}}\right)^{-1} {\rm G} \tag{3}$$

Note that for a continuously emitting source the time delay could be source intrinsic in which case we can only impose the constraint $\alpha_{\rm rms} \lesssim 2.5^\circ$, leading to the less stringent constraint

$$B \lesssim 5 \times 10^{-10} \left(\frac{l_c}{1\,{\rm Mpc}}\right)^{-1/2} \left(\frac{r}{30\,{\rm Mpc}}\right)^{-1/2} {\rm G} . \tag{4}$$

The constraints Eq. (3) and in particular Eq. (4) for bursting sources are considerably more stringent than the existing upper limit on a coherent, all-pervading field of 10^{-9} G, coming from Faraday-rotation measurements (Kronberg 1994). If the charged particle would be produced as a heavy nucleus, its charge would decrease on the way to the observer by partial or complete photodisintegration in the CMB (Puget, Stecker, & Bredekamp 1976). In that case the bounds Eqs. (3) and (4) would become even stronger by at least a factor Z_f, where Z_f is the charge of the nucleus upon arrival at the observer.

If observed galactic magnetic fields cannot be explained by a galactic dynamo (Kulsrud & Anderson 1992), one might expect protogalactic fields of strength $10^{-12} - 10^{-9}$ G with a coherence scale of order 1 Mpc, depending on the way this field is compressed during galaxy formation (Kulsrud et al. 1995). A bound such as Eq. (3) would then considerably constrain such a scenario. An all-pervading field would have to be $\lesssim 10^{-12}$ G, whereas stronger fields could not permeate intergalactic space uniformly. Correlations between UHE CR events might therefore offer a means to constrain the EGMF in a way which is complementary to other recently suggested methods (Plaga 1995; Lee, Olinto, & Sigl 1995; Sigl, Lee, & Coppi 1996a).

In case of bursting sources, we can thus assume that the observed deflection is dominated by the galactic magnetic field. If we assume this field to be coherent over a scale l_g, its strength being B_g, we obtain for $E = 50$ EeV

$$\alpha \simeq 1.1^\circ\, Z \left(\frac{l_g}{1\,{\rm kpc}}\right) \left(\frac{B_g}{10^{-6}\,{\rm G}}\right) \sin\theta , \tag{5}$$

for a nucleus of charge Ze, where θ is the angle between the field polarization and the arrival direction of the particle. In addition, since the time delay in the galactic magnetic fields is bounded by the observed time delay $\tau \simeq 2\,\mathrm{yr}$, we obtain from $\tau \simeq \alpha^2 l_g/2$

$$l_g \lesssim 1 \left(\frac{\alpha}{2^\circ}\right)^{-2} \mathrm{kpc} \tag{6}$$

The numbers in Eqs. (5) and (6) are quite consistent with observational knowledge on the galactic magnetic field parameters, $l_g \simeq$ hundreds of pc, $B_g \simeq 3\times10^{-6}\,\mathrm{G}$ (Vallee 1991). In addition, the observed polarization of the coherent component of the galactic field predicts the arrival directions of lower energy protons to be of lower galactic latitude than the ones of the higher energy particle (Sigl, Schramm, & Bhattacharjee 1994). Within the experimental angular resolution this is consistent with the pairs observed by AGASA. Furthermore, using standard values for the galactic magnetic field parameters, Eq. (5) shows that it is unlikely that the clustered events have been caused by heavy nuclei with Z greater than a few. The relative deflection of such nuclei would typically be substantially larger than 1° at the energies under consideration.

3. Implications for Ultra-High-Energy Cosmic Ray Production Scenarios

It was mentioned that two of the three pairs observed by AGASA lie within $\simeq 10^\circ$ of the supergalactic plane. That seems to suggest an origin in some conventional sources associated with the large scale structure such as powerful galaxy clusters or AGN. Since no such object was identified as an obvious source, the situation with regard to conventional shock acceleration models remains inconclusive at the present time. It has also been noted recently (Waxman, Fisher, & Piran 1996) that a strong concentration of UHE CRs towards the supergalactic plane would be inconsistent with a correlation with the known large scale structure.

This raises the question about the perspectives of alternative models to explain possible correlations between events with energy slightly below and above 60 EeV. In this energy range the most readily detectable particles are γ-rays and nucleons whose range is limited to less than $\simeq 100\,\mathrm{Mpc}$ (see, e.g., Lee 1996). The AGASA experiment is approximately sensitive to a cone with opening angle $\simeq 45^\circ$ around the zenith. Since under our assumptions time delays in the EGMF are comparable to or smaller than the inverse rate of observed pairs $\simeq 1\,\mathrm{yr}$, the rate of bursts f_b causing these pairs must obey $f_b \sim 1.6\times10^{-6}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$. The combined integral flux above 100 EeV from Fly's Eye (Bird et al. 1994) and AGASA (Yoshida et al. 1995) is $J(100\,\mathrm{EeV}) \simeq 5\times10^{-21}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$. From this, we can obtain a rough estimate of the necessary energy release E_b per burst,

$$E_b \simeq \frac{4\pi E J(E)}{\lambda(E) f_b} \simeq 6.3\times10^{49}\left(\frac{\lambda(E)}{30\,\mathrm{Mpc}}\right)^{-1}\left(\frac{J(100\,\mathrm{EeV})\cdot\mathrm{cm}^2\,\mathrm{sr}\,\mathrm{s}}{5\times10^{-21}}\right)\left(\frac{f_b\cdot\mathrm{Mpc}^3\,\mathrm{yr}}{1.6\times10^{-6}}\right)^{-1}\mathrm{erg}\,, \tag{7}$$

where $\lambda(E)$ is the attenuation length of the particle species dominating the observed flux.

In relativistic fire ball models of GRBs the time scale for proton acceleration is limited by the dissipation radius $r_d \lesssim \gamma_b^2 t_\gamma \lesssim 2.9\times10^{-3}(\gamma_b/300)^2\,\mathrm{yr}$, where γ_b is the Lorentz factor of the expanding fire ball and $t_\gamma \sim 1\,\mathrm{s}$ is the observed duration of the (low energy) γ-ray burst. Thus, in these models the release time scale of UHE CRs is indeed short compared to the time delay in the observed pairs. However, the rate of cosmological GRBs, $f_\gamma \simeq 3\times10^{-8}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ (Cohen & Piran 1995), violates the above condition $f_b \sim 1.6\times10^{-6}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$. This condition can only be circumvented if charged UHE CRs are delayed by at least 50 yr during propagation, most probably by deflection in a large scale EGMF (Waxman 1995a,b). Confirmation of typical time delays in clustered events as small as a few years would thus most likely rule out this type of cosmological GRB models as an explanation for such clusters. This is in analogy to the fact that confirmation of recently claimed positional coincidences between highest energy cosmic rays and strong GRBs (Milgrom & Usov 1995) would rule out an origin of UHE CRs in cosmological GRBs. In that case, an association of UHE CRs with GRBs would at best be possible if GRBs were situated in the galactic halo (Vietri 1995b), an option which might soon be ruled out by an increasing data set on GRBs. This could well hint to the existence of exotic sources which are neither linked to ordinary prominent astrophysical objects nor to GRBs.

Let us now assume that the burst sources consist of topological defects. For example, certain classes of cosmic string loops might collapse and release all of their energy in form of UHE CRs within about one light crossing time t_b (Bhattacharjee & Rana 1990). If v is the symmetry breaking scale associated with the phase transition in which the string was formed, $t_b \simeq 2.6\,(E_b/6.3\times10^{49}\,\mathrm{erg})(v/10^{23}\,\mathrm{eV})^{-2}\,\mathrm{s} \ll 1\,\mathrm{yr}$ and thus the "burst condition" is fulfilled.

It remains to determine the UHE CR composition predicted by TD models. We have recently performed extensive numerical simulations for the propagation of extragalactic nucleons, γ-rays, and electrons with energies between $10^8\,\mathrm{eV}$ and $10^{25}\,\mathrm{eV}$ through the universal low energy photon background (Lee 1996; Sigl, Lee, & Coppi 1996a,b). All relevant interactions have been taken into account, including synchrotron loss in the EGMF of the electronic component of the electromagnetic cascades which result from UHE γ-ray injection into the universal radiation background. Here, we assume an EGMF of $2\times10^{-12}\,\mathrm{G}$ which obeys the constraint Eq. (3). Time averaged predictions from a representative TD model are shown in Fig. 1. Since for the burst rates suggested by the clustering observed by AGASA at any time roughly one burst contributes to the flux above a few tens of EeV, the UHE fluxes at these energies are representative for a typical burst induced by a topological defect at a distance $\simeq 50-100\,\mathrm{Mpc}$. The flux normalization was optimized to allow for an explanation of the highest energy events observed and corresponds to a likelihood significance for this fit of $\simeq 0.95$ above 100 EeV (including all bins where no events have been detected; for details see Sigl et al. 1995). The flux below a few tens of EeV is presumably produced by conventional shock acceleration. The γ-ray flux below $\sim 10^{14}\,\mathrm{eV}$ only depends on the total energy release integrated over redshift which, for a given TD model and cosmological history of energy release, is then determined by the flux normalization at UHEs. It can clearly be seen that the scenario shown in Fig. 1 is consistent with current data and bounds on γ-ray and UHE CR fluxes. For more details on constraints on TD models see Sigl, Lee, & Coppi 1996a,b; Sigl et al. 1995. Fig. 1 shows that events above $\simeq 80\,\mathrm{EeV}$ are predicted to be most likely γ-rays, whereas around 50 EeV an approximately equal amount of protons is expected from the TD induced bursts. About one fifth of the total observed flux at these energies would be due to protons from the TD induced bursts, in rough agreement with the two observed pairs out of 20 events above 50 EeV (clusters of pure γ-rays within a timescale roughly given by the burst itself should, of course, eventually also be seen in this scenario for sufficiently high total exposure). Since an electromagnetic cascade particle (i.e. a γ-ray or an electron) is deflected and delayed equally or less strongly than a proton at the same energy, this scenario is clearly consistent with the discussion of the previous section. We also note that the muon content of the showers observed by AGASA is not in contradiction with interpreting the higher energy event in the pairs as a γ-ray (Hayashida et al. 1996).

4. Conclusions

We discussed the consequences of a possible clustering of a subset of UHE CR events above $\simeq 40$ EeV which was recently reported by the AGASA experiment. If the observed time delay of low relative to high energy events of $\simeq 2$ yr is typical, the correlated events might originate in a burst on a timescale shorter than ~ 1 yr, the observed time delay being caused by deflection in magnetic fields. If the real angular deviation between clustered events is not much smaller than 1° (which currently cannot be excluded because the angular resolution of the AGASA experiment is comparable to the observed deviation), deflection of charged particles by the EGMF should be negligible and can be exclusively attributed to the galactic magnetic field, provided the charge is smaller than a few times the proton charge. This would substantially improve existing limits on the EGMF. Scenarios where the magnetic fields observed in galactic disks originate from an EGMF of strength $10^{-12} - 10^{-9}$ G with coherence length scales of $\simeq 1$ Mpc would be constrained considerably. This could possibly indicate that such protogalactic fields cannot be primordial, i.e. permeate all of intergalactic space.

The typical time delay of $\simeq 2$ yr between lower and higher energy events within a cluster suggested by AGASA is in conflict with models which associate such events with cosmological GRBs. Conventional shock acceleration models require identification of a prominent astrophysical object as a source candidate within a few degrees of the arrival directions of the events. No obvious identification could be made for the event clusters observed. This might hint to the operation of a TD type mechanism where part of the UHE events would be related to new fundamental physics near the grand unification scale. In such a scenario, events below and above $\simeq 80$ EeV could be mostly nucleons and γ-rays, respectively, if the EGMF is $\lesssim 10^{-11}$ G and the event pairs observed by AGASA could be produced in bursts on timescales less than $\simeq 1$ yr. This is similar to the cosmological GRB scenario, but with a higher burst rate per volume or, correspondingly, a lower energy release per burst. This possibility is currently not ruled out by any data.

Future instruments in construction or in the proposal stage such as the Japanese Telescope Array (Teshima et al. 1992), the High Resolution Fly's Eye (Bird et al. 1995b), and the Pierre Auger Project (Cronin 1992) will have the potential to test whether there is significant clustering of UHE CRs. The latter experiment, with an angular resolution of a fraction of 1° and an energy resolution of $\simeq 10\%$, should detect tens of event clusters per year if the clustering observed by AGASA is real.

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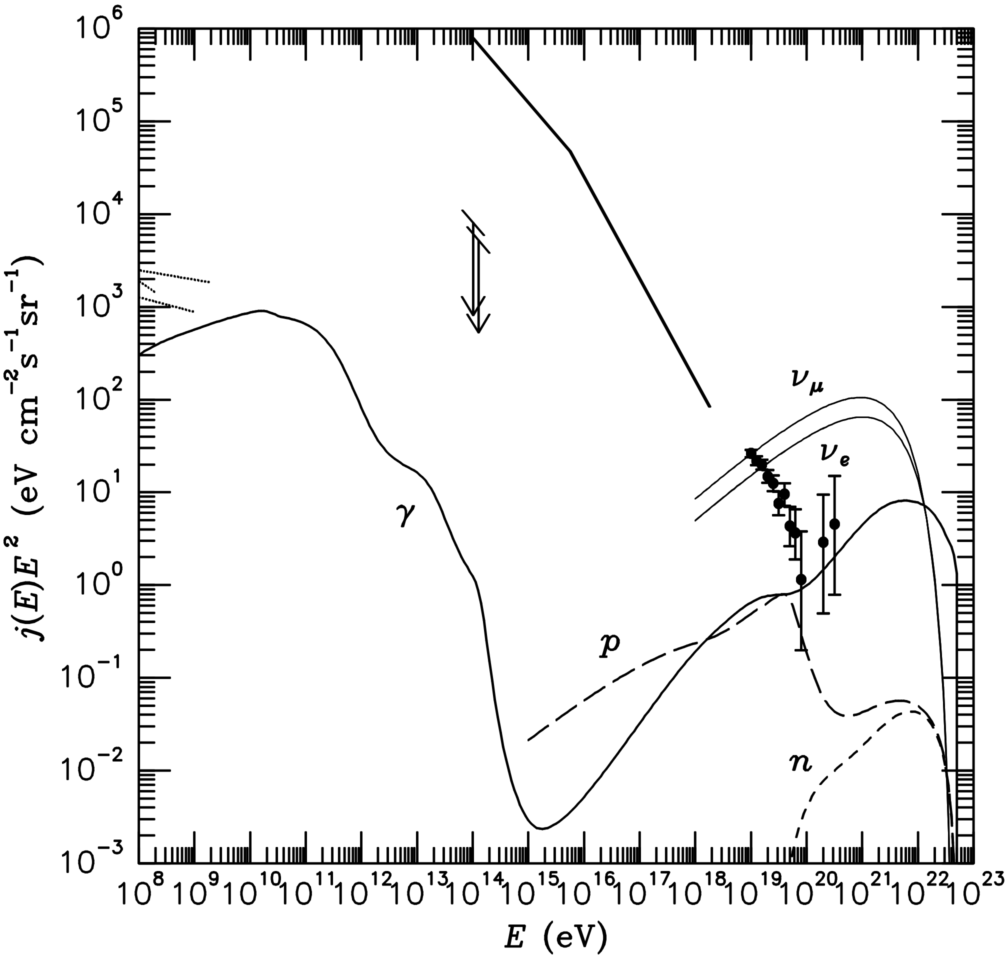

Fig. 1.— Predictions for the differential fluxes of γ-rays (solid line), protons (long dashed line) and neutrons (short dashed line) above 10^{15} eV and muon and electron neutrinos (thin solid lines in decreasing order) above 1 EeV by a typical TD scenario. These fluxes are time averaged or, equivalently, for spatially uniform injection. About 3% of the total energy is injected as nucleons, 30% as γ-rays, and the rest as neutrinos with a spectrum roughly $\propto E^{-1.5}$ up to $E = 10^{23}$ eV (for more details about the model and the simulations see Sigl, Lee, & Coppi 1996a). The average modulus of the EGMF amplitude was assumed to be 2×10^{-12} G. Also shown are the combined data from the Fly's Eye (Bird et al. 1993, 1994) and the AGASA (Yoshida et al. 1995) experiments above 10 EeV (dots with error bars), piecewise power law fits to the observed charged CR flux (thick solid line) and experimental upper limits on the γ-ray flux below 10 GeV from Digel, Hunter, & Mukherjee 1995, Fichtel et al. 1977, and Osborne, Wolfendale, & Zhang 1994 (dotted lines on left margin in decreasing order). The arrows indicate limits on the γ-ray flux from Karle et al. 1995. Implications for the interpretation of event clusters originating in TD induced bursts are discussed in the text.