Gamma rays precursors and afterglows surrounding UHECR events: Z-burst model is still alive

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The Z-burst model and the direct propagation of UHE proton in negligible extragalactic magnetic fields produce gamma-rays afterglows and precursors halos, respectively at GeVs and TeV energy band a few degree around the UHECR arrival direction. The possible correlation of UHECR clusters (doublet, triplet) with nearby BL Lac sources at $E_p \approx 4 \cdot 10^{19}$ eV offer a test for this necessary Gamma-UHECR trace. We estimate the secondary gamma energy and spectra and we suggest how to disentangle between the different scenarios. We show why Z-Burst model is still the most realistic model to explain UHECR behaviour and their correlation to known BL Lac sources.

1. Introduction

The UHECR events with energy above $4 \times 10^{19}$ eV are bounded by the primordial photon drag (the well known GZK cut-off) in a very narrow universe ($\sim 50$ Mpc). Because of their charge UHECR are bent and blurred by cosmic magnetic fields. However, UHECR because of their extremely rigidity maintain their primordial arrival direction. Surprisingly, there aren’t any nearby known galactic structures or super-galactic objects correlated with these UHE events which can accelerate protons at so high energy. Recent AGASA evidence of UHECR events clustering toward some BL Lacs (see table I) seems to confirm a cosmic extra-galactic origin of UHECR from compact sources. So there is a puzzle to solve: if these UHECR (just at the edge of GZK cut off energies) are protons (as experimental data suggest), how can they point to their primary BL Lac sources (often at large distance) with a small ($< 2.5^\circ$) angular dispersions? There are two mechanisms to solve this puzzle: the rectilinear propagation of UHE proton from the source to the Earth (proposed by Berezinsky) within negligible extragalactic magnetic fields and the Z-burst model [1], [2] (based on UHE ZeV neutrino scattering on relic light neutrinos in hot dark halos). Both the processes mainly lead, as a by product, to a signal respectively in TeV (direct flight) and GeV (Z-Burst) photons. These photons can be observed either as afterglows or as precursors of the UHECR events. They may be (respectively) long lived showers (direct flight) of a few years or months or prompt signals (Z-Burst) within days or hours. In the following, we will study these two different models and we will show that direct proton flight call for unobserved TeV tails while the Z-burst model is still the most competitive and realistic process to solve the GZK puzzle because it agrees with the observed GeV gamma tails along the BL Lac Sources correlated to UHECR cluster events.

2. The rectilinear propagation of UHECR

The rectilinear propagation of UHECR protons is possible only if the intergalactic magnetic field is extremely weak. The actual knowledge of the intergalactic magnetic field is still very poor.

Usually, extragalactic magnetic fields are characterized by an average strength $B$ and by a coherence length $l_c$ which means that its power spectrum has a cut-off at the wavelength space $k = 2\pi/l_c$.

Neglecting the energy losses for the moment, the r.m.s. deflection angle over a distance $d$ in
Table 1
BL Lacs correlated with UHECR. We focus and remind among the (14) clusters here only those (9) BL Lacs whose distance is above \(z=0.1\) and whose energy is well defined.

| EGRET name | Possible BL Lac | l (°) | b (°) | Redshift z |
|------------|----------------|-------|-------|------------|
| 0433+2908  | 2EG J0432+2910* | 170.5 | -12.6 | -          |
| 0808+5114  | 1ES 0806+524*   | 166.2 | 32.91 | 0.138      |
| 1009+4855  | GB 1011+496     | 165.5 | 52.71 | 0.2        |
| 1222+2841  | ON 231*         | 201.7 | 83.29 | 0.102      |
| 1424+3734  | TEX 1428+370    | 63.95 | 66.92 | 0.564      |
| 1052+5718  | RGB J1058+564*  | 149.6 | 54.42 | 0.144      |
| 1605+1553  | PKS 1604+159*   | 29.38 | 43.41 | -          |
| 2352+3752  | TEX 2348+360    | 109.5 | -24.91| 0.317      |
| 1052+5718  | RGB J1058+564*  | 149.6 | 54.42 | 0.144      |

such field is \[^3]\:

\[
\vartheta(E, d) \simeq \frac{(2dl_c/9)^{1/2}}{R_L} \simeq 0.8^\circ (E_{20})^{-1/2} (l_{c1})^{1/2} (B_{\perp -9})
\]

where \(E_{20}\) is the energy of the proton, \(E_p = 10^{20}\) eV, \(d_{10}\) is the distance, \(d = 10\) Mpc and \(l_{c1} = 1\) Mpc. It should be noticed that a Galactic Magnetic field \(B_G \approx \mu\text{Gauss}\) and a coherent length of \(l_c \approx 100\) pc, within a galactic size of \(d \approx 10\) kpc already implies an angular rms of the order \(\vartheta(E, d) \approx 2.4^\circ\). The deflection implies also an average time delay, \(\tau\), relative to rectilinear propagation:

\[
\tau(E, d) \simeq \frac{d \vartheta(E, d)}{4c} \simeq 1.5 \times 10^3 \left(\frac{E}{10^{13}\text{eV}}\right)^{-2} \left(\frac{d}{1000\text{Mpc}}\right)^2 \cdot \left(\frac{l_c}{10\text{Kpc}}\right) \left(\frac{B_\perp}{10^{-11}\text{G}}\right)^2 \text{ yr}
\]

The Galactic Magnetic field \(B_G \approx \mu\text{Gauss}\) and as before a coherent length of \(l_c \approx 100\) pc, a galactic size of \(d \approx 10\) kpc already implies a time dilation of the order \(\tau(E, d) \approx 15\) yrs. Berezinsky required \[^2\], for having rectilinear propagation of UHECR with an energy \(E \sim 10^{19}\) eV from a distance \(d \sim 1000\) Mpc, that the angular deflection produced by the magnetic field is not larger than the angular resolution of sources in the detectors (typically \(\vartheta_{res} = 2.5^\circ\)). According to equation \[^1]\) this request gives an upper limit to the strength of a magnetic field with a small coherence length \(l_c = 10\) Kpc:

\[
B \leq 3 \times 10^{-10}\text{G}
\]

For a proton with an energy \(E_p = 4 \times 10^{19}\) eV the relevant mechanism of energy losses is the photo electron pair production with the photons of the Cosmic Microwave Background (CMB). In the following we refer to the electron and to the positron as electron. The electron pairs are produced by a virtual photon of characteristic energy:

\[
\hbar \varpi = \frac{4}{3} \gamma^2 (\hbar \omega)_{CMB}
\]

\[
\sim 1.35 \cdot 10^{18} (\hbar \omega)_{CMB} \left(\frac{E_p}{4 \cdot 10^{19}\text{eV}}\right)^2 \text{ eV}
\]

where \(\gamma\) is the Lorentz factor of protons and \(\hbar \omega_{CMB}\) is the average energy of \(\gamma_{CMB}\) that is \(6.34 \times 10^{-4}\) eV. The electron will have half of the energy of this photon i.e.:

\[
E_{\varepsilon_1} = \frac{1}{2} \hbar \varpi \sim 6.8 \times 10^{17}\text{eV} \left(\frac{E_p}{4 \cdot 10^{19}\text{eV}}\right)^2
\]
At this energy and in the center of moment (mass) frame system, the electron will behave nearly as a massless particle because the quantity

\[ E_{\text{cms}} = 11.2 \left( \frac{\hbar \omega_{\text{CMB}}}{6.8 \times 10^{17}} \right)^{1/2} \text{ TeV} \]  

is \( \gg m_e \). So the electron will distribute half of his energy to a new electron \( e_2 \) and half to a new photon \( \gamma_2 \). The \( \gamma_2 \) will produce a new pair of \( e^+e^- \) while the \( e_2 \) will produce a new \( \gamma_3 \) and a new \( e_3 \).

This process will form an electromagnetic shower by I.C.S.-pair production and (in analogy to the Heitler for normal showers in atmosphere) it will continue since \( E_{\text{cdm}} \sim m_e \); it will happen for a transition energy around \( E_e = 7.5 \times 10^{13} \) eV.

For this energy, we have an effective Inverse Compton scattering that will produce only photons with an energy lower and lower than the incoming electron:

\[ \hbar \omega = \frac{4}{3} \gamma^2 (\hbar \omega_{\text{CMB}}) \]

\[ \sim 3.23 \cdot 10^{11} (\hbar \omega_{\text{CMB}}) \left( \frac{E_e}{10^{13} \text{eV}} \right)^2 \text{ eV} \]  

The energy fraction given by electron to the photon reduces itself as the process goes on: the final result is the production (and the consequent pilling up) of TeV photons; the electron pairs progenitors aren’t much deviated by the necessary small extragalactic magnetic field: in fact, the electrons are very collimated with the proton directions until \( E_e = 10^{15} \) eV because their Larmor’s radius is much smaller than their energy losses (by I.C.S.) length. After this energy, their Larmor’s radius is:

\[ R_L = 20 \left( \frac{B}{10^{-11} \text{G}} \right)^{-1} \left( \frac{E}{10^{14} \text{eV}} \right) \text{Kpc} \]  

and so their deviation is still quite negligible respect to their short life time distance by ICS with the CMB \( \lambda_e \sim c \tau_e \sim 5(E/10^{14} \text{eV})^{-1} \text{Kpc} \). This can be seen in figure 1 and in figure 2 that describe the process of halving and the ICS respectively for electrons and photons. The TeV photons might suffer of an additional and partial (for Hundreds or Mpc distances) IR cut-off; but mostly these TeV traces might survive and arrive for a long times (years) collinear with the UHECR event. This TeV-UHECR connection, (except for a questionable mild TeV clustering around \( T E X 1428+370 \)) is not observed in known (Milagro [1]) map.

### 3. The Z-burst model

A different solution of the UHECR puzzle above the GZK cut-off, able to explain also the BL Lacs correlation with UHECR, is based on light relic neutrino masses in hot halo, a wide calorimeter for UHE neutrinos messengers. The interaction between an extragalactic ZeV UHE neutrino and a halo of relics neutrinos with a fixed mass may produce Z-resonance whose boosted decay in flight leads to the observable UHECR nucleons (proton, anti-protons, neutron, anti-neutrons). In the s-channel the interaction of neutrinos of the same flavor occurs by Z-exchange:
Figure 2. Qualitative representation of the energy’s halving and ICS processes for photons; we also trace by different colors the Larmor radius for $B = 10^{-12} G$ and $B = 10^{-9} G$ and by dotted lines the energy losses for synchrotron radiation.

Figure 3. Zeta resonance and main secondaries for $m_\nu = 0.4$

$\nu\bar{\nu} \rightarrow Z^*$ (see figure 3). The cross section of this reaction shows a peak due to the resonant $Z$-production at $s = M_Z^2$; this $Z$-resonance (here averaged on the energy) requires an initial neutrinos energy $E_\nu \sim 10^{22} (m_\nu/0.4 eV)^{-1} eV$ to produce a proton with energy $E_p \sim 2.2 \times 10^{20} (m_\nu/0.4 eV) eV$ (see table 2). It’s important to evidence that a $m_\nu \sim 0.4 eV$ gives a relic neutrino number density:

$$n_{\nu}\sim 4.725 \times 10^2 \left(\frac{m_\nu}{0.4 eV}\right)^3 \left(\frac{V}{300km/s}\right)^3 \text{ cm}^{-3}$$

for halo’s size $l \sim 30 Mpc$, compatible with a Local Super Cluster. So we have a number density contrast $\sim 8$ above cosmic background ($n_{\nu}^0 \sim 56 cm^{-3}$). A similar contrast is also available for a mean neutrino velocity 2 times larger (corresponding to our Sun motion in the Black Body Radiation) and a relic neutrino mass as small as half ($m_\nu \sim 0.2 eV$) the assumed one. This light mass is better comparable with observed atmospheric neutrino’s mass splitting ($\Delta m \sim 0.05 eV$). Non degenerated lightest neutrino masses ($m_\nu \lesssim 0.1 eV$) would lead to multi-bump uhecr modulation at highest energy ($[4], [5]$).

A proton, with energy $E_p = 2.2 \times 10^{20} eV$ at a distance of 30 Mpc, suffers the $\gamma_{\text{CMB}}$ opacity and loses for photo-pair production a factor $e^{2.6} = 13.46$ of its initial energy. So there is a degradation of proton’s energy around $E_{fp} \sim 10^{19} eV$: this energy is compatible with the energy of UHECR clustered events correlated with the observed BL Lacs in table 3. At the $Z$-resonance we have also the production of UHE electrons with energy $E_e \sim 2 \times 10^{19} eV$ due to charged pions decay. Assuming an extragalactic magnetic field $B = 10^{-9} G$ (according to experimental measure of Faraday rotation and CMB anisotropy), the electrons interaction with it will lead to $E_{\gamma} = 27.2 GeV$ photons direct peak:

$$E_{\gamma}^{\text{sym}} = \frac{3}{2} \gamma^2 \left(\frac{eBh}{m_e}\right)$$

$$\sim 27.2 \left(\frac{E_e}{2 \times 10^{19} eV}\right)^2 \left(\frac{m_\nu}{0.4 eV}\right)^{-2} \left(\frac{B}{nG}\right) GeV$$

This mechanism is effective and fast and it gives gamma-rays afterglows and precursors of UHECR events. In fact, we have an immediate emission of photons to tens of GeV as soon as the electron
interacts with the extragalactic magnetic field and a subsequent emission of GeV photons until the electron arrives at an energy $\sim 1.9 \times 10^{18}$eV. At those energies the synchrotron radiation is leading to $E_{\gamma} \sim 270$ MeV emission. After this point, the dominant process will be Inverse Compton scattering: ICS leads to an electromagnetic cascade to TeV energies in analogy (but at a much lower level) to what occurred for the UHE proton-electron pair showering in the Berezinsky scenario.

In the Z-burst, there is a marginal (3.3%) production of direct UHE electron pairs with $E \sim 5 \times 10^{23}$eV that create PeV photons for synchrotron’s radiation:

$$E_{\gamma} = 1.7 \left( \frac{E_e}{5 \cdot 10^{21} \text{eV}} \right)^2 \left( \frac{m_\nu}{0.4 \text{eV}} \right)^{-2} \left( \frac{B}{nG} \right) \text{PeV} \quad (10)$$

Nevertheless, this process is less significative and probable than the process explained above for UHE electrons in the s-channel. Also these PeV photons are screened and degraded by CMB cut off, to TeV energy band. In fact, these photons will produce $e^+e^-$ pairs for interaction with $\gamma_{CMB}$: the electrons will have an energy $E_e \sim 0.85$ PeV and they will produce via synchrotron radiation with the extragalatic magnetic field $B = 10^{-9}$ G photons with energy:

$$E_{\gamma} = 50B^{-9} \left( \frac{E_e}{0.85 \cdot 10^{15} \text{eV}} \right)^2 \left( \frac{m_\nu}{0.4 \text{eV}} \right)^{-2} \text{eV} \quad (11)$$

Nevertheless, we must remember that because of $\rho_{B-9} \sim 10^{-7}\rho_{CMB}$ the energy losses are essentially given by ICS as for the Berezinsky scenario and, in conclusion, we have the sequent process $E_{\gamma} \rightarrow e^+e^- \rightarrow E_{1C}$ that transforms the $e^+e^-$ energy to TeV photons with an efficacy $\eta \sim 3/24 \sim 12.5\%$ of the Z-boson’s energy.

4. Z-burst vs. UHE rectilinear propagation

It’s important to evidence some problems of the rectilinear propagation of UHE:

1. if we consider the BL Lacs correlated with UHECR, we see that the sources, of which we know the energy and the redshift, are all above the proton’s length for photo pair production (see table 3). This requires that the real energies of events (also neglecting the photo-pion production) are shifted towards higher energies: consequently, the UHE proton will cross a greater distance and will produce more $e^+e^-$ pairs. These pairs will produce a so great number of TeV photons that could exceed the present experimental limit on TeV energies. Moreover, the last two events in table 3 after this shift, have an energy bigger of that required for the Z-burst model ($E_{Z-burst} = 10^{22}$ eV).

2. The charged assignments of the first two events for which the correlation occurred is zero or negative.

So a proton can’t explain it.

3. In this model we have mainly a TeV gamma-ray afterglow halo surrounding the UHECR event because the life time of an electron with an energy $E_e = 10^{14}$eV (that produces TeV photons on BBR by ICS) is

$$\tau_e \sim \frac{2.8 \times 10^{12}}{\gamma} \text{yr} \sim 1.5 \times 10^4 \left( \frac{E}{10^{14} \text{eV}} \right)^{-1} \text{yr} \quad (12)$$

which, compared with the proton’s time of delay given by eq. 2, is even longer. The electron pair tail in the direct as well Z-Burst model is very narrow bounded along the UHECR propagation. Therefore the gamma ring-halo afterglow is well collimated along UHECR path.

The Z-burst’s advantages on the contrary are:

1. explanation of the correlation between UHECR and BL Lacs, without any charge problems (UHECR maybe either proton or neutron or their anti-particles);

2. production of gamma-rays precursors and afterglows tails around GeV energy where
there aren’t strong experimental bounds but even some positive evidence shown in correlation with EGRET GeV identified sources,

3. UHECR calibration with the observed light neutrino masses (0.4 – 0.1 eV), well within known atmospheric mass splitting, naturally located in an extended hot dark halo within GZK distance,

4. time delay arrival between the UHECR cluster compatible with observation and with the expected extra-galactic magnetic fields.

Therefore, in conclusion, the Z-burst model is offering pion decays and gamma GeV signature by synchrotron radiation whose presence is already found in EGRET; any direct flights of UHECR from distant BL Lac are often in disagreement with the charge sign observed and they call even for very high TeV flux halo; we have shown in present article that TeV signals, whose fluence might be comparable or larger than UHECR fluxes, are absent in present data. Therefore in our opinion, the Z-Burst is at present the most realistic model to explain UHECR events: we believe that a possible prompt observation of gamma-rays afterglows surrounding UHECR at MeV-GeV or at TeV energies will test these two models. We suggest therefore a fast search by MAGIC, HESS and VERITAS telescopes within a short time scales (minutes-hours-days or weeks) toward the UHECR arrival directions, looking for GeVs-TeVs showering halo (electromagnetic imprint of Z-decay in flight and its synchrotron emission) surrounding the UHECR event. Also X-Ray search by high resolution X-ray satellites as Chandra pointing promptly toward UHECR arrivals directions might find exciting signatures of the shower afterglow along the particle path.

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Table 2
Secondaries produced in the interaction $\nu\bar{\nu} \rightarrow Z$, assuming $E_\nu = 10^{22} \text{ eV}$, an incoming energy neutrino fluence $F_\nu = 2000 \text{ eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ and a relic neutrino mass $m_\nu = 0.4 \text{ eV}$; the neutrino interaction probability corresponds to 1%.

| Multiplicity | Energy(%) | $\sum E_{CM}(\text{GeV})$ | Peak energy (EeV) | $\frac{dN}{dE}E^2(eV)$ |
|--------------|-----------|-----------------|------------------|-----------------------|
| p            | 2.7       | 6%              | 5.4              | $2.2 \times 10^2$    | 1.2                   |
| $\pi^0$      | 13        | 24%             | 19.25            | $1.9 \times 10^2$    | 4.25                  |
| $\gamma_{\pi^0}$ | 26   | 21.4%           | 19.25            | 95                    | 4.25                  |
| $\pi^\pm$    | 26        | 42.8%           | 38.5             | $1.9 \times 10^2$    | 4.25                  |
| $(e^+e^-)_\pi$ | 26  | 12%             | 11               | 50                    | 2.3                   |
| $(e^+e^-)_{prompt}$ | 2  | 3.3%            | 2.7              | $10 \times 10^3$     | 1.32                  |
| $(e^+e^-)_\mu$ | 2  | 1.1%            | 0.9              | $1.6 \times 10^3$    | 0.45                  |
| $(e^+e^-)_\tau$ | 2  | 1.5%            | 1.3              | $1.2 \times 10^3$    | 0.6                   |

Table 3
BL Lacs and their real energies

| EGRET Name   | $z$  | d (Mpc) | $E_{obs}(10^{19} \text{eV})$ | $E_{in}(10^{19} \text{eV})$ | Charge assignment |
|--------------|------|---------|-----------------------------|-----------------------------|-------------------|
| 0808+5114    | 0.138| 455     | 3.4                         | 9.2                         | 0                 |
| 1052+5718    | 0.144| 475     | 7.76                        | 14.7                        | 0,-1              |
| 1424+3734    | 0.564| 1861    | 4.97                        | $6 \times 10^3$             | 0,+1              |
| 1850+5903    | 0.53 | 1750    | 5.8                         | $10^4$                      | +1                |