Comment on " Cosmological Gamma Ray Bursts and the Highest Energy Cosmic Rays"

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In a letter with the above title, published some time ago in PRL, Waxman [1] made the interesting suggestion that cosmological gamma ray bursts (GRBs) are the source of the ultra high energy cosmic rays (UHECR). This has also been proposed independently by Milgrom and Usov [2] and by Vietri [3]. However, here I show that the recent data from AGASA [4], which does not show the suppression in the intensity of cosmic rays (CR) at energy beyond$\sim 4\times 10^{19} eV$ that was predicted by Greisen, Zatsepin and Kuz'min (GZK) for extragalactic cosmic rays due to their interaction with the cosmic background photons [5], rules out extragalactic GRBs as the source of UHECR.

For simplicity, consider first a uniform distribution of galaxies (or sites of GRBs) in Euclidean space, with a number density n per unit volume. Let ΔE_{CR} be the mean energy release in CR per GRB and R_G the GRB rate per galaxy. Neglecting scattering and attenuation in the intergalactic space, the contribution of such sources within a distance D from Earth to the observed CR energy flux (energy per unit area, per sr, per unit time) is

$$S \approx \frac{nR_G\Delta E_{CR}D}{4\pi}~. \tag{1}$$

Cosmic expansion and evolution are unimportant for cosmological distances $D \ll c/H \sim 3000h^{-1}\ Mpc$ where $H = 100h\ km\ s^{-1}\ Mpc^{-1}$. If UHECR are trapped locally by (unknown) strong extragalactic magnetic fields that surround our Milky Way galaxy, then D in eq. 1 must be replaced by $c\tau(E)$, where $\tau(E)$ is the lifetime of UHECR in the trap due to attenuation and/or escape by diffusion in the magnetic fields. The mean attenuation length (lifetime) of CR with energies above $4 \times 10^{19} eV$ (the GZK "cutoff" energy) due to photoproduction in collisions with the cosmological background photons yields [6] $D < 15\ Mpc$ ($\tau < 5 \times 10^8\ y$). The attenuation of CR protons below the GZK "cutoff" energy is mainly due to e^+e^- pair production on the cosmic background photons. The attenuation length (time) Just below the GZK "cutoff" energy is [6] $D \sim 1000\ Mpc$ ($\tau \sim 3 \times 10^{10}\ y$). It increases with decreasing energy to the Hubble radius (Hubble time) at about $10^{18.5} eV$, the energy of the CR ankle. Since D ($c\tau$) changes at the GZK "cutoff" energy by a factor $\geq 1000/15 \sim 70$, the intensity of the UHECR flux beyond the GZK "cutoff" is suppressed by the same factor. Such a suppression was not observed by AGASA [4].

Moreover, GRBs that emit isotropically and are uniformly distributed within $D < 20\ Mpc$ cannot produce the measured intensity of UHECR above the CR ankle: The measured luminosity density in the local Universe is [7] $n \sim 1.8h \times 10^8 L_\odot\ Mpc^{-3}$. From the observed rate of cosmological GRBs [8], $R_{obs} \sim 10^3\ y^{-1}$, and from the recently measured/estimated redshifts of some GRBs and host galaxies of GRBs [9], it was concluded that [10] $R_* < 10^{-8}\ y^{-1}$ per $L_* \sim 10^{10} L_\odot$ galaxy. The kinetic energy release in UHECR per birth/death of compact stellar objects, which are the plausible triggers of GRBs in galaxies, probably, does not exceed [11] $\Delta E_{CR} \sim 10^{52}\ erg$ (Waxman's assumption, $\Delta E_{CR} = 5\epsilon \times 10^{50}\ erg$ where ϵ is the mean energy of UHECR in $10^{20} eV$ units, makes the discrepancy even larger). Thus, for $h \sim 0.65$, eq. 1 yields an energy flux of UHECR,

$$S \sim 30 \left(\frac{n}{1.8h \times 10^{-2} Mpc^{-3}}\right) \left(\frac{R_G}{10^{-8} y^{-1}}\right) \left(\frac{\Delta E_{CR}}{10^{52} erg}\right) \left(\frac{D}{20 Mpc}\right)\ eV\ m^{-2} s^{-1} sr^{-1}. \tag{2}$$

The CR above the ankle have an approximate power-law spectrum [4] $dn/dE \approx AE^{-\beta}$ with $\beta \sim 2.5$. Even in the very unlikely situation where the bulk of the GRB energy is carried by CR with energy above $E_0 \sim 10^{20} eV$, one obtains from eq. 2 that for $E \sim E_0$

$$E^3 \frac{dn}{dE} \sim (\beta - 2) S E_0 \left(\frac{E}{E_0}\right)^{1-\beta} \sim 3 \times 10^{21} eV^2 m^{-2} s^{-1} sr^{-1}. \tag{3}$$

The observed value [4], $E^3 dn/dE \sim 4 \times 10^{24} eV^2 m^{-2} s^{-1} sr^{-1}$ around $E \sim E_0$, is smaller by three orders of magnitude than that predicted by eq. 3. The above luminosity problem can be solved by postulating that GRBs emit isotropically more than 10^{55} erg in UHECR (very unlikely), or by jetting the GRB ejecta [11]. If the GRB ejecta is collimated into a narrow jet (plasmoid) with a bulk motion Lorentz factor $\Gamma \sim 10^3$ then its radiation is beamed into a solid angle $\Delta\Omega \sim \pi/\Gamma^2$. The "isotropic" energy release, $E_{isot} \equiv 4\pi(\Delta E/\Delta\Omega) = (4\pi/\Delta\Omega)\Delta E \sim 4\times 10^6(\Gamma/10^3)^2\Delta E$, can be much larger than ΔE, the true energy release in GRB. Thus, while the total luminosity, $R_{obs}E_{isot}$, from GRBs, is independent of the beaming angle, E_{isot} can be much larger than that assumed by Waxman [1] and Vietri [3]. However, extragalactic GRBs cannot smear the GZK "cutoff" unless there is a "cosmic conspiracy", namely, the large scale local magnetic fields conspire to trap the extragalactic UHECR at the GZK "cutoff" energy for a time which is approximately equal to their attenuation time in the background radiation [12]. Such a possibility also seems very remote in view of observational limits on extragalactic magnetic fields from limits on Faraday rotation of radio waves from distant powerful radio sources [13] and from limits on intergalactic synchrotron emission: The Larmor radius of $4\times 10^{19} eV$ protons in typical extragalactic magnetic fields, ($B < 10^{-9} G$), is much larger than the typical coherence length ($l_c < 1\ Mpc$) of these fields. Moreover, magnetic trapping is completely ruled out if the arrival directions of UHECR coincide with the directions of cosmological GRBs [2] or if the arrival directions of extragalactic UHECR are clustered [14]. Thus, if extragalactic CR protons below the GZK "cutoff" suffer only small random magnetic deflections through intergalactic space and reach us from distances as far as $D \sim 1000\ Mpc$ away, then their flux must show the the GZK suppression when their energy increases beyond $\sim 4\times 10^{19} eV$.

The same arguments can be repeated for cosmic ray nuclei which are attenuated via photodissociation by cosmic background radiations. They lead to the same conclusion, namely, the UHECR which are observed near Earth, most probably, are not produced by extragalactic GRBs. However, narrowly collimated Galactic GRBs, most of which do not point in our direction, can be the source of non solar cosmic ray nuclei at all energies [15,16].

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