Signatures of AGN model for UHECR

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We demonstrate that the energy spectra of Ultra High Energy Cosmic rays (UHECR) as observed by AGASA, Fly’s Eye, HiRes and Yakutsk detectors, have the imprints of UHE proton interaction with the CMB radiation in the form of the dip at \( E \sim 1 \times 10^{19} \) eV, of the beginning of the GZK cutoff, and of very good agreement with calculated spectrum shape. We argue that these data, combined with small-angle clustering and correlation with AGN (BL Lacs), point to the AGN model of UHECR origin at energies \( E \gtrsim 1 \times 10^{20} \) eV. Our consideration includes also the case when correlation with BL Lacs is excluded from the analysis. The excess of the events at \( E > 1 \times 10^{20} \) eV, which is observed by AGASA (but absent in HiRes data) can be explained by another component of UHECR, e.g. by UHECR from superheavy dark matter.

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The nature of signal carriers and of the sources of UHECR are not yet established (for recent reviews see \textsuperscript{[1,2,3]}). The most natural primary particles are extragalactic protons. Due to interaction with the CMB radiation the Ultra High Energy (UHE) protons from extragalactic sources are predicted to have a sharp steepening of energy spectrum, so called GZK cutoff \textsuperscript{[4]}. For uniformly distributed sources, the GZK cutoff is characterized by energy \( E_{1/2} \) where the integral spectrum calculated with energy losses taken into account becomes twice lower than the power-law extrapolation from low energies, \( E_{1/2} = 5.3 \times 10^{19} \) eV \textsuperscript{[3]}. The particles with energies higher than \( 1 \times 10^{20} \) eV are undoubtably observed. There are at least two “golden” events at energies \( 2 - 3 \times 10^{20} \) eV \textsuperscript{[3]} with very reliable energy determination (see also discussion in Ref. \textsuperscript{[3]}). However, the real contradiction with the existence of the GZK cutoff is observed only by AGASA (see Fig.\textsuperscript{1}). Data of HiRes \textsuperscript{[3]} are in good agreement with presence of the GZK cutoff (Fig. 1). The data of other detectors are not as conclusive, though a few events with energy higher than \( 1 \times 10^{20} \) eV are observed there (see \textsuperscript{[1]} for a review and \textsuperscript{[3]} for recent discussion).

In this Letter we shall demonstrate that the observed spectra have the imprints of UHE proton interaction with the CMB radiation in the form of the dip at the energy \( E \sim 1 \times 10^{19} \) eV, produced by \( p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^- \) interaction, in the form of the beginning of the GZK cutoff, and in the form of good agreement between predicted and observed spectra. We argue that at least at energies up to \( 1 \times 10^{20} \) eV the data (spectrum, small-scale clustering \textsuperscript{[3]} and probably the correlation with BL Lacs sources \textsuperscript{[3]} can be explained in the model with AGN as the sources of UHE protons.

Calculating the spectra, we shall use the cosmological parameters as follows from recent observations \textsuperscript{[13]}: flat universe with \( \Omega_{\text{tot}} = 1 \) and \( \Omega_{\Lambda} = 0.7 \). At small redshifts \( z \), neutrinos, baryons and CDM behave as non-relativistic matter with \( \Omega_{\text{m}} = 0.3 \). We shall use the Hubble constant \( H_0 = 70 \) km/s Mpc. The relation between time and redshift is given by

\[
dt = \frac{dz}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_{\Lambda}}}.
\]

The spectrum of UHE protons in the model with uniform distribution of the sources and with the power-law generation spectrum can be calculated using the formalism of Ref. \textsuperscript{[3]}, with the continuous energy losses from Refs. \textsuperscript{[14,15]} (note the difference in formulae due to cosmology with \( \Lambda \) term):

\[
J_0(E) = (\gamma_g - 2) \frac{c}{4\pi H_0} \frac{L_0}{\Omega_m(1+z)^3 + \Omega_{\Lambda}} \frac{dz_g(1+z_g)^{m-1}}{\sqrt{\Omega_m(1+z_g)^3 + \Omega_{\Lambda}}} \times \left[ E_g(E, z_g) \right]^{-\gamma_g} \frac{dE_g(z_g)}{dE}.
\]

where \( z_m \) is a maximum redshift in the evolution of the sources, \( z_g \) is a redshift at generation and \( E_g(z_g) \) is energy of a proton at generation, for
present \((z = 0)\) energy \(E\); \(\mathcal{L}_0 = n_0 L_p\) is cosmic ray (CR) emissivity at \(z = 0\) \((n_0\) and \(L_p\) are space density of the sources and their CR luminosity, respectively). As the general case we assume cosmological evolution of the sources given by \(\mathcal{L}(z) = \mathcal{L}_0 (1 + z)^m\), where the absence of evolution corresponds to \(m = 0\). All energies in Eq.\([2]\) are given in GeV and luminosities in GeV/s. Dilation of energy interval is given by \([5]\), modified by Eq.\([1]\) as

\[
\frac{dE_c(z)}{dE} = (1 + z_g) \times \exp \left[ \frac{1}{\theta_0} \int_0^{z_g} \frac{dz (1+z)^2}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \left( \frac{db_0(E')}{dE} \right) \right]
\]

where \(b_0(E) = dE/dt\) is the energy loss due to interaction with CMB photons at \(z = 0\). Derivative \(db_0(E')/dE\) at \(z = 0\) (given in Ref.\([14]\)) is taken at energy \(E' = (1 + z) E_g(E, z)\).

For particles with energies \(E \gtrsim 1 \times 10^{17} \text{eV}\), the maximum redshift for evolution of CR sources \(z_m\) is not important if it is larger than 4. In Fig.1 the calculated spectra are compared with the data of AGASA, HiRes, Fly’s Eye and Yakutsk detectors. Note that the theoretical spectra are the same in all four panels. We assume the generation spectrum \(\propto E^{-2}\) at \(E \leq E_c\) and \(\propto E^{-\gamma_g}\) at \(E \geq E_c\) with a spectrum cutoff at \(E_{\text{max}}\). The calculations for this case are easily generalized from Eq.\([2]\), as it is done by Eq.\([10]\) from Ref.\([14]\). As parameters we have chosen \(E_{\text{max}} = 1 \times 10^{18}\) eV, \(E_c = 1 \times 10^{18}\) eV, \(\gamma_g = 2.7\) for non-evolutionary \((m = 0)\) model and \(\gamma_g = 2.5\) for evolutionary \((m = 3)\) model. The required CR emissivity for both models is \(\mathcal{L}_0 \approx (2.5 - 3.5) \times 10^{46}\) ergs/Mpc³/yr. The choice of \(E_c\) is motivated by the observed chemical composition. We assume that transition to extragalactic component occurs at the observed second knee \([6]\), \([3]\), at \(E_2 \approx 4 \times 10^{17}\) eV. The observed rigidity cutoff for protons, \(E/Z = (4 - 5) \times 10^{15}\) eV according to KASCADE data \([19]\), [20], corresponds to the cutoff energy for iron nuclei \(E \approx 1 \times 10^{17}\) eV. Remaining gap \((1 - 4) \times 10^{17}\) eV can be filled by ultra-heavy nuclei with charge up to \(Z = 92\) \([21]\). The transition to the lighter chemical composition with a large fraction of protons has been observed at \(E > 3 \times 10^{17}\) eV by AGASA \([21]\), FE \([16]\), Yakutsk \([18]\) and HiRes \([17]\) detectors. The data of HiRes \([22]\) show that at \(E \gtrsim 6 \times 10^{17}\) eV the protons can be the dominant component.

![Fig. 1. The calculated spectra for non-evolutionary model (full lines), with parameters indicated in the text. Both curves were first normalized to adjusting the emissivity \(\mathcal{L}_0\). To fit the data of HiRes, Fly’s Eye and Yakuts factors 0.63, 0.80, and 1.7, respectively.](image)

Fig.1 shows that that the signatures of interaction of UHE protons with the CMB radiation, the dip and the beginning of the GZK cutoff, are seen in the data.

The most natural sources of the observed UHE protons are AGN. The required CR emissivity meet well the local emissivity of AGN, e.g. that of Seyfert galaxies is of order \(\mathcal{L}_{\text{Sy}} \sim n_{\text{Sy}} L_{\text{Sy}} \sim 1 \times 10^{48}\) ergs Mpc³/yr. The protons can be accelerated in AGN up to energies of order \(\sim 10^{21}\) eV \([23]\). An interesting possibility is acceleration in the jets by unipolar induction \([24]\). The correlation of UHECR with BL Lacs \([12]\), i.e. with AGN whose jets are directed towards us, strongly supports this mechanism.

Two sets of observational data favor rectilinear propagation of UHE signal carriers in the universe. The first set is the above-mentioned correlation \([12]\) with BL Lacs. The second one is the small-
angle clustering \[1\]. Its most natural interpretation is given \[23\] in terms of statistically occasional arrival of two or three particles from a compact source. Such an interpretation needs rectilinear propagation of the primaries and large number of sources \[24\].

Since the proton origin of UHECR is almost proved, the correlation with BL Lacs directly implies the rectilinear propagation of UHE protons. Thus, these correlations become supersensitive tools to measure extragalactic magnetic fields. Below we shall discuss what is the scale of this field and whether this field can be already excluded.

Magnetic field must not produce the angular deflection larger than angular resolution of sources in the detectors, which is typically \(\theta_{\text{res}} \approx 2.5^\circ\). The correlation is found in the energy range \((4 - 8) \times 10^{19} \text{ eV}\), for which the largest attenuation length is \(l_{\text{att}} \approx 1000 \text{ Mpc}\). The required upper limit for the magnetic field, which is homogeneous on this scale, is \(B_l \leq 2 \times 10^{-12}/l_{1000}^1 \text{ G}\), where \(l_{1000}\) is attenuation length for \(4 \times 10^{19} \text{ eV}\) protons in units of 1000 Mpc. For a magnetic field with small homogeneity length \(l_{\text{hom}}\) the required upper limit is

\[
B \leq \frac{E \theta_{\text{res}}}{e \sqrt{l_{\text{att}} l_{\text{hom}}}} \approx 6 \times 10^{-10} \text{ G},
\]

where the numerical value is given for \(l_{\text{att}} \sim 1000 \text{ Mpc}\) and \(l_{\text{hom}} \sim 10 \text{ kpc}\).

We argue that these fields are not excluded. The observed Faraday rotations give only the upper limits on large scale extragalactic magnetic field \[26\]. All known mechanisms of generation of the large scale cosmological magnetic field results in extremely weak magnetic field \(\sim 10^{-17} \text{ G}\) or less (for a review see \[27\]). The strong magnetic field can be generated in compact sources, presumably by dynamo mechanism, and spread away by the flow of the gas. These objects thus are surrounded by magnetic halos, where magnetic field can be estimated or measured. The strong magnetic fields of order of \(1 \mu \text{G}\) are indeed observed in galaxies and their halos, in clusters of galaxies and in radiolobes of radiogalaxies. As an example one can consider our local surroundings. Milky Way belongs to the Local Group (LG) entering the Local Supercluster (LS). LG with a size \(\sim 1 \text{Mpc}\) contains 40 dwarf galaxies, two giant spirals (M31 and Milky Way) and two intermediate size galaxies. The galactic winds cannot provide the appreciable magnetic field inside this structure. LS with a size of \(10 - 30 \text{ Mpc}\) is a young system where dynamo mechanism cannot strengthen the primordial magnetic field. In fact LS is filled by galactic clouds submerged in the voids. The vast majority of the luminous galaxies reside in a small number of clouds: 98% of all galaxies in 11 clouds \[25\]. Thus, accepting the hypothesis of generation of magnetic fields in compact sources, one arrives at the perforated picture of the universe, with strong magnetic fields in the compact objects and their halos (magnetic bubbles produced by galactic winds) and with extremely weak magnetic fields outside. However, even in this picture there is a scattering of UHE protons off the magnetic bubbles and the scattering length is \(l_{\text{sc}} \sim 1/\pi R^2 n\), where \(R\) is the radius of magnetic bubble and \(n\) is their space density. Among different structures, the largest contribution is given by galaxy clusters which can provide \(l_{\text{sc}} \sim (1 - 2) \times 10^3 \text{ Mpc}\).

Leaving the correlation of UHECR with AGN (BL Lacs) as an open problem for future observations we turn now to the alternative of excluding these correlations from analysis. The small-angle clustering then can be probably explained in the other extreme case of very strong magnetic field due to lensing effect \[29\]. Rectilinear propagation of UHE protons is not needed anymore.

Till now we discussed mostly UHECR at \(E \lesssim 1 \times 10^{20} \text{ eV}\). At higher energies, as AGASA data show, there might be an excess of events. They should be interpreted as the new component. One possibility is given by Superheavy Dark Matter (SDMP) \[30\]. The spectrum of UHE particles, produced at the SHDM decay is now reliably calculated using the different methods \[31\]. All calculations give very similar spectrum with \(\gamma_g \approx 1.9 - 2.0\). This spectrum is shown in Fig.1. It describes well the observed AGASA excess. The primary particles are predicted to be UHE photons, which at energy \(E > 1 \times 10^{20} \text{ eV}\) cannot be excluded by available experimental data, in particular by the inclined Haverah Park showers \[32\].

In conclusion, the observed energy spectra reveal the signatures of interaction of UHE protons with the CMB in the form of the dip, beginning of the GZK cutoff and the good agreement with the predicted spectrum. Combined with small-angle clustering \[1\] and correlation with BL Lacs \[12\], these data require the rectilinear propagation of UHE protons and AGN as their sources. The correlation with AGN (BL Lacs) becomes thus the most sensitive method of measuring very weak extragalactic magnetic fields. In case this correlation is not confirmed by future observational
data, and the small-angle clustering is explained by some more sophisticated phenomena (e.g. by magnetic lensing), AGN remain the favorable UHECR sources, but as one of the possible candidates.

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