Is the HiRes Energy Spectrum Really Consistent with GZK Cutoff?

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Abstract

Ultra-high energy cosmic ray (UHECR) protons produced by uniformly distributed astrophysical sources contradict the energy spectrum measured by *both* the AGASA and HiRes experiments, assuming the small scale clustering of UHECR observed by AGASA is caused by point-like sources. In that case, the small number of sources leads to a sharp exponential cutoff at the energy $E < 10^{20}$ eV in the UHECR spectrum [5].

The HiRes experiment published recently its data from monocular observations [1]. They showed that the UHECR flux is consistent with the GZK cutoff expected for *uniformly, continuously* distributed sources. As a result, the simplest model of UHECR—protons accelerated in uniformly distributed, extragalactic sources—seems to be a convincing explanation of their data. The authors of Ref. [2] found as fingerprints of the expected interactions of UHE protons with CMB photons a dip at $E \sim 1 \times 10^{19}$ eV, a bump and the beginning of the cutoff in the measured spectra of four UHECR experiments. The agreement of the spectral shape calculated for protons with the measured spectra is excellent, apart from an excess in the AGASA data above $E \geq 8 \times 10^{19}$ eV. These findings point to an AGN origin of UHECR below $E \leq 10^{20}$ eV and to protons as primaries. Despite the fact that the AGASA experiment sees a significant number of events above the GZK cutoff [8], the model of proton primaries from extragalactic sources looks very attractive, because it does not require new physics.

The model of uniformly, *continuously* distributed sources is based on the assumption that the number of UHECR sources is so large that a significant fraction of sources is inside the GZK volume. However, as it was shown in a number of works [3,4,8], the small scale clustering of UHECR observed by AGASA allows to estimate the number of UHECR sources assuming that their distribution

pp. 651–654

and luminosity is known. In the model of homogeneous distribution of sources with equal luminosity, the estimate for the number of sources [3] is

$$S \approx \frac{\overline{N}_{\rm tot}^3}{\overline{N}_{\rm cl}^2}\,, \tag{1}$$

where $\overline{N}_{\rm tot}$ is the total number of observed events and $\overline{N}_{\rm cl}$ is the number of events in clusters. In Eq. (1), it is assumed that $\overline{N}_{\rm tot} \gg \overline{N}_{\rm cl}$.

We show now that the statement that UHECRs with $E \geq 10^{20}$ eV are protons from nearby sources is in contradiction to the total number of sources estimated including events below the GZK cutoff. Following [3,4], we use 14 events with $E > 10^{20}$ eV and one doublet. Then Eq. (1) gives $S_{\rm GZK} \sim 700$ sources in the GZK volume. Protons with $E \sim 4 \times 10^{19}$ eV propagate at most from redshift $z = 0.2$, or $R_{\rm tot} \sim 1000$ Mpc (see, e.g., Fig. 2 in [7]). Conservatively assuming that all events with $E > 10^{20}$ eV come from within the GZK distance $R_{\rm GZK} = 50$ Mpc (in [3,4] $R_{\rm GZK} = 25$ Mpc was used), the expected number of sources of all events with energy $E \geq 4 \times 10^{19}$ eV is $S_{\rm tot} = (R_{\rm tot}/R_{\rm GZK})^3 S_{\rm GZK} \approx 5.6 \times 10^6$. We should compare this number with the one directly calculated from the AGASA data [8,9] with $E \geq 4 \times 10^{19}$ eV. We have $\overline{N}_{cl} = 13$ (6 doublets and triplet) and $\overline{N}_{\rm tot} = 59$. Then Eq. (1) gives $S_{\rm AGASA} \sim 1200$. Since the Poisson probability to observe $S_{\rm AGASA}$ instead of $S_{\rm tot}$ events is practically zero, the chance probability to obtain these two event numbers is equal to the chance probability of clustering. We conclude therefore that the model in which *all* UHECR with $E \geq 4 \times 10^{19}$ eV are protons from uniformly distributed point sources is inconsistent with the small scale clustering observed by AGASA.

One can argue that 14 UHECR events with $E > 10^{20}$ eV is an optimistically high number and that the real number of such events is much smaller because the experiments estimate wrongly the energy of UHECR events. We conservatively take only the four highest energy events from all experiments, including one Fly's Eye event, two AGASA events and one HiRes event. In this case we have 4 single events and no doublets. We can estimate the number of sources, if we conservatively assume that tomorrow one doublet will be observed in those data, i.e. $\overline{N}_{\rm cl} = 2$ and $N_{\rm tot} = 5$. Thus, there are $S \sim 30$ sources in the GZK volume with $R_{\rm GZK} = 50$ Mpc. Again, in a volume with $R_{\rm tot} \sim 1000$ Mpc there are $S \sim 240.000$ sources, in comparison with up to 1200 required by AGASA data above $E \geq 4 \times 10^{19}$ eV. Thus, if the clustered component in the AGASA events with energy $E \geq 4 \times 10^{19}$ eV is due to point-like sources, the expected number of sources is of the order of $S_{\rm AGASA} \sim 1200$. These sources are distributed in a volume with $R_{\rm tot} \sim 1000$ Mpc. Thus, the expected number of sources in GZK volume is $S_{\rm GZK} \leq 0.1$, or the distance to nearest source is $R_{\rm min} \sim 100$ Mpc.

Let us now discuss the consequences of a small number of sources for the model of uniformly, continuously distributed point sources of protons. For our

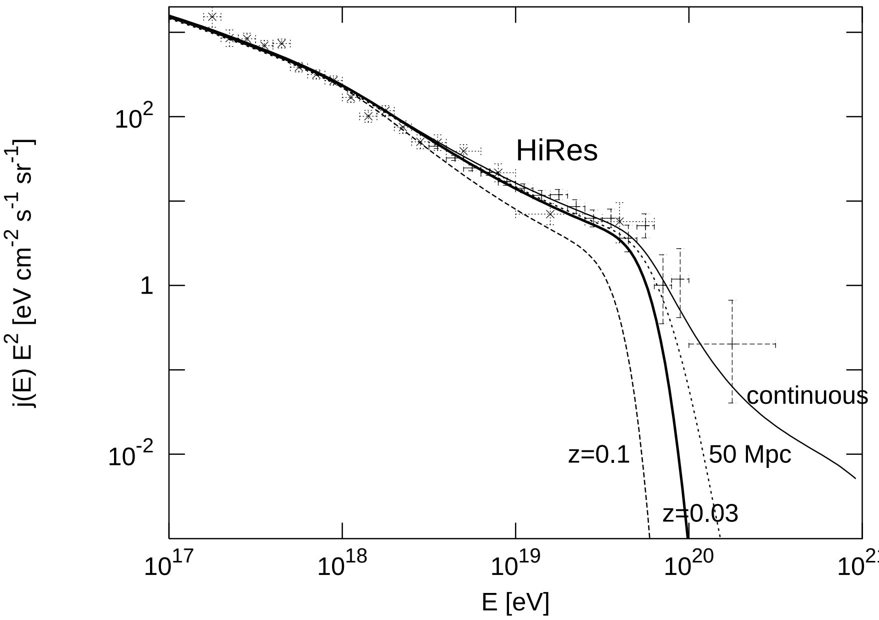

Fig. 1. UHECR flux measured by the HiRes experiment [1]. The thin solid line corresponds to an uniform, continuous distribution of proton sources in the Universe with emission spectrum $1/E^{2.7}$ and $E_{\rm max} = 10^{21}$ eV. The dotted curve is for the same model, but with no sources within 50 Mpc from the Earth. The thick solid line corresponds to no sources within $z_{\rm min} = 0.03$, the dashed line to $z_{\rm min} = 0.1$.

calculations, we have used the code developed in Ref. [6], in which all important effects (pion production, e^+e^- production and the expansion of the Universe) are taken into account. In Figs. 1. and 2. we show with thin solid lines the spectrum of continuously distributed sources of protons with emission spectrum $1/E^{2.7}$ and $E_{\rm max} = 10^{21}$eV as in Ref. [2]. Let us concentrate on Fig. 1., which shows the measured spectrum of HiRes and where the fit model of [2] with an infinite number of sources (thin solid line) works well. If there are no sources within 50 Mpc (dotted curve), the two highest HiRes data points are well above the model fit. The minimum distance of $z_{\rm min} = 0.03$ corresponds to the BL Lac distribution, potential UHECR sources suggested in [10]. Then two additional experimental points are away from the fit in this case. Finally, for an uniform distribution of 1200 sources over the Universe, or $z_{\rm min} = 0.1$, the disagreement above the cutoff becomes even worse. Note that we are only concerned about energies above $\sim 6 \times 10^{19}$ eV; at lower energies, the quality of the fitted model can be easily improved by a readjustment of the fit parameters. The same figure with experimental data from AGASA is shown in Fig. 2..

Thus, if the clustered component of the AGASA data for $E \geq 4 \times 10^{19}$ eV (which has a statistical significance of 4.6σ) is not a statistical fluctuation or

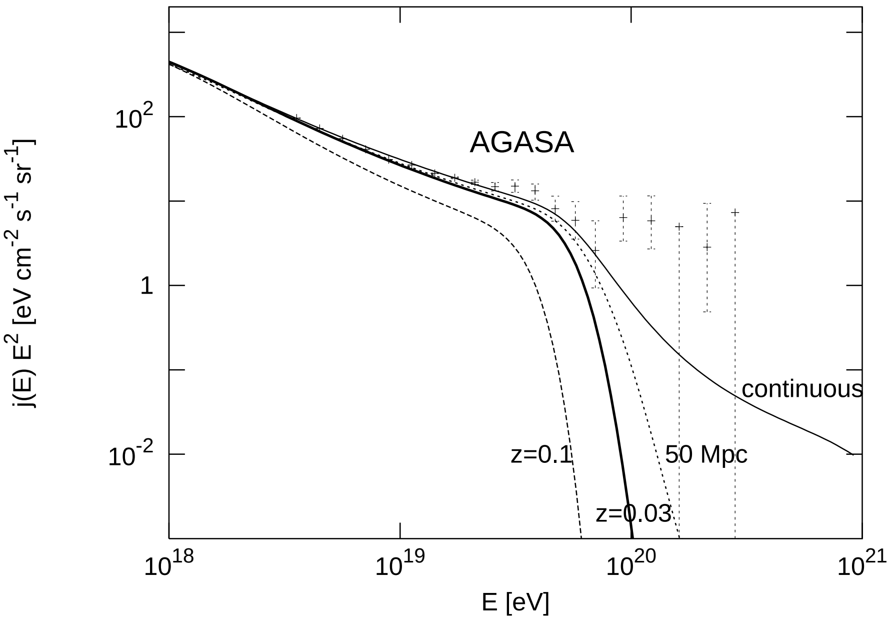

Fig. 2. UHECR flux measured by the AGASA experiment [8]. All other parameters are the same as in Fig. 1..

the result of magnetic lensing, the expected relative small number of UHECR sources is inconsistent with the model of proton primaries emitted by uniformly continuously distributed sources both for the HiRes and AGASA data. This means that *both* the AGASA and HiRes data require the introduction of a new component (not protons) in the UHECR spectrum. In the paper [5] we suggested that such new component can be fitted with exotic hadrons.

1. References

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