GZK Horizons and the Anisotropy of Highest-energy Cosmic Ray Sources

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Motivated by recent Pierre Auger result on the correlation of the highest-energy cosmic rays with the nearby active galactic nuclei, we explore possible ultrahigh energy cosmic ray (UHECR) source distributions and their effects on GZK horizons. Effects on GZK horizons by local over-density of UHECR sources are examined carefully with constraints on the degree of local over-density inferred from the measured UHECR spectrum. We include the energy calibration effect on the Pierre Auger data in our studies. We propose possible local over-densities of UHECR sources which are testable in the future cosmic ray astronomy.

1 Introduction

Recently, Pierre Auger observatory published results on correlation of the highest-energy cosmic rays with the positions of nearby active galactic nuclei (AGN)\textsuperscript{11}. Such a correlation is confirmed by the data of Yakutsk\textsuperscript{2} while it is not found in the analysis by HiRes\textsuperscript{3}. In the Auger result, the correlation is maximal for the threshold energy of cosmic rays at $5.7 \times 10^{19}$ eV, the maximal distance of AGN at 71 Mpc and the maximal angular separation of cosmic ray events at $\psi = 3.2^\circ$. Due to increasing efforts on verifying the Auger result, it is worthwhile to examine the above correlation from a phenomenological point of view.

Since the angular scale of the observed correlation is a few degrees, one expects that these cosmic ray particles are predominantly light nuclei. The effect of GZK attenuations on these cosmic ray particles\textsuperscript{4,5} can be described by a distance scale referred to as “GZK horizon”. By definition, the GZK horizon associated with a threshold energy $E_{\text{th}}$ is the radius of a spherical region which is centered at the Earth and produce 90% of UHECR events arriving on Earth with energies above $E_{\text{th}}$.

Assuming a uniform distribution of UHECR sources with identical cosmic ray luminosity and spectral index\textsuperscript{6}, the GZK horizon for protons with $E_{\text{th}} = 57$ EeV is about 200 Mpc while the V-C catalog\textsuperscript{7} used by Pierre Auger for the correlation study is complete only up to 100 Mpc. Such a deviation may arise from non-uniformities of spatial distribution, intrinsic luminosity and spectral index of local AGN as mentioned in\textsuperscript{11}. In addition, the energy calibration also plays a crucial role since the GZK horizon is highly sensitive to the threshold energy $E_{\text{th}}$. Energy values corresponding to the dip and the GZK cutoff of UHECR spectrum were used to calibrate energy scales of different cosmic ray experiments\textsuperscript{8,9}. It has been shown that all measured UHECR energy spectra can be brought into good agreements by suitably adjusting the energy scale of each experiment\textsuperscript{8}. Furthermore, it has been shown that a different shower energy
reconstruction method infers a 30% higher UHECR energy than that determined by Auger’s fluorescence detector-based shower reconstruction\[^{10}\].

In this presentation, we report our results\[^{11}\] on examining the consistency between Auger’s UHECR correlation study and its spectrum measurement. The impact by the local over-density of UHECR sources is studied. We also study the energy calibration effect on the estimation of GZK horizon and the spectrum of UHECR. Certainly a 20% – 30% upward shift on UHECR energies reduces the departure of theoretically calculated GZK horizon to the maximum valid distance of V-C catalog\[^{1}\]. The further implications of this shift will be studied in fittings to the shifted Auger spectrum.

2 GZK horizons and the UHECR spectrum

Table 1: GZK horizons of UHECR calculated with the local over-density \(n(l < 30 \text{ Mpc})/n_0 = 1, 2, 4, \text{ and } 10\), and arrival threshold energy \(E_{\text{th}} = 57 \text{ EeV, } 70 \text{ EeV, } 80 \text{ EeV and } 90 \text{ EeV respectively. The listed numbers are in units of Mpc.}\)

| \(n(l < 30 \text{ Mpc})/n_0\) | \(E_{\text{th}} = 57 \text{ EeV}\) | \(E_{\text{th}} = 70 \text{ EeV}\) | \(E_{\text{th}} = 80 \text{ EeV}\) | \(E_{\text{th}} = 90 \text{ EeV}\) |
|---|---|---|---|---|
| 1 | 220 | 150 | 115 | 90 |
| 2 | 210 | 140 | 105 | 75 |
| 4 | 195 | 120 | 85 | 60 |
| 10 | 155 | 85 | 50 | 30 |

GZK horizons corresponding to different local over-densities and \(E_{\text{th}}\) are summarized in Table I. Within the same \(E_{\text{th}}\), local over-densities up to \(n(l < 30 \text{ Mpc})/n_0 = 4\) do not significantly alter GZK horizons. One could consider possibilities for higher local over-densities. However, there are no evidences for such over-densities either from astronomical observations\[^{12}\] or from fittings to the measured UHECR spectrum. We note that GZK horizons are rather sensitive to \(E_{\text{th}}\). Table I shows that GZK horizons are \(\sim 100 \text{ Mpc or less for } E_{\text{th}} \geq 80 \text{ EeV.}\)

Fittings to the Auger spectrum have been performed in\[^{13}\]. In our work, we take into account the over-density of UHECR sources in the distance scale \(l \leq 30 \text{ Mpc.}\) The local over-density of UHECR sources affects the cosmic-ray spectrum at the highest energy, especially at energies higher than \(5 \cdot 10^{19} \text{ eV.}\) Hence the degree of local over-density can be examined through fittings to the measured UHECR spectrum.

Table 2: The values of total \(\chi^2\) from fittings to the Auger measured UHECR spectrum. Numbers in the parenthesis are \(\chi^2\) values from fittings to the 8 data points in the energy range \(19.05 \leq \log_{10}(E/\text{eV}) \leq 19.75.\) The last 4 data points record events with energy greater than \(71 \text{ EeV.}\)

| \(n(l < 30 \text{ Mpc})/n_0\) | 1 \(\gamma = 2.5\) | 2 \(\gamma = 2.5\) | 4 \(\gamma = 2.5\) | 10 \(\gamma = 2.5\) |
|---|---|---|---|---|
| | 14.12(9.34) | 14.61(9.93) | 17.09(10.50) | 28.09(13.93) |
| | 16.64(12.28) | 15.56(11.90) | 16.01(11.83) | 20.76(11.67) |

Table 3: The total \(\chi^2\) values from fittings to the Auger measured UHECR spectrum with a 30% upward shift on UHECR energies. Numbers in the parenthesis are \(\chi^2\) values from fittings to the 8 data points in the energy range \(19.16 \leq \log_{10}(E/\text{eV}) \leq 19.86.\) The last 4 data points record events with energy greater than \(92 \text{ EeV.}\)

| \(n(l < 30 \text{ Mpc})/n_0\) | 1 \(\gamma = 2.4\) | 2 \(\gamma = 2.4\) | 4 \(\gamma = 2.4\) | 10 \(\gamma = 2.4\) |
|---|---|---|---|---|
| | 8.65(4.30) | 7.39(4.67) | 10.26(6.35) | 27.31(13.34) |
| | 11.82(6.16) | 8.67(5.49) | 7.78(5.23) | 16.18(7.39) |
The left panel in Fig. 1 shows our fittings to the Auger measured UHECR spectrum with $\gamma = 2.5$ and 2.6 respectively. We take the red-shift dependence of the source density as $n(z) = n_0(1 + z)^m$ with $m = 3$. We have fitted 12 Auger data points beginning at the energy $10^{19}$ eV. We make a flux normalization at $10^{19}$ eV while varying the power index $\gamma$ and the degree of local over-density, $n(l < 30 \text{Mpc})/n_0$. Part of $\chi^2$ values from our fittings are summarized in Table II. We found that $\gamma = 2.5$, $n(l < 30 \text{Mpc})/n_0 = 1$ gives the smallest $\chi^2$ value with $\chi^2/\text{d.o.f.} = 1.57$. For the same $\gamma$, $n(l < 30 \text{Mpc})/n_0 = 10$ is ruled out at the significance level $\alpha = 0.001$. For $\gamma = 2.6$, $n(l < 30 \text{Mpc})/n_0 = 10$ is ruled out at the significance level $\alpha = 0.02$. We note that, for both $\gamma = 2.5$ and $\gamma = 2.6$, the GZK horizon with $n(l < 30 \text{Mpc})/n_0 = 10$, $E_{\text{th}} = 57$ EeV, $m = 3$ and $E_{\text{cut}} = 1000$ EeV is about 155 Mpc. Since $n(l < 30 \text{Mpc})/n_0 = 10$ is clearly disfavored by the spectrum fitting, one expects a GZK horizon significantly larger than 155 Mpc for $E_{\text{th}} = 57$ EeV.

We next perform fittings to the shifted Auger spectrum. The results are shown in the right panel in Fig. 1 where the cosmic ray energy is shifted upward by 30%. Part of $\chi^2$ values are summarized in Table III. The smallest $\chi^2$ value occurs approximately at $\gamma = 2.4$, $n(l < 30 \text{Mpc})/n_0 = 2$ with $\chi^2/\text{d.o.f.} = 0.82$. One can see that $\chi^2$ values from current fittings are considerably smaller than those from fittings to the unshifted spectrum. Given a significance level $\alpha = 0.1$, it is seen that every local over-density listed in Table III except $n(l < 30 \text{Mpc})/n_0 = 10$ is consistent with the measured UHECR spectrum. It is intriguing to test such local over-densities as will be discussed in the next section. We note that, with a 30% upward shift of energies, the cosmic ray events analyzed in Auger’s correlation study would have energies higher than 74 EeV instead of 57 EeV. The GZK horizon corresponding to $E_{\text{th}} = 74$ EeV is 120 Mpc for $n(l < 30 \text{Mpc})/n_0 = 2$ and 105 Mpc for $n(l < 30 \text{Mpc})/n_0 = 4$.

We have so far confined our discussions at $m = 3$. In the literature, $m$ has been taken as any number between 0 and 5. It is demonstrated that the effect on UHECR spectrum caused by varying $m$ can be compensated by suitably adjusting the power index $\gamma$. Since GZK horizons are not sensitive to $\gamma$ and $m$, results from the above analysis also hold for other $m$’s.

3 Discussions and conclusions

We have discussed the effect of local over-density of UHECR sources on shortening the GZK horizon. The result is summarized in Table I. It is seen that such an effect is far from sufficient to shorten the GZK horizon at $E_{\text{th}} = 57$ EeV to $\sim 100$ Mpc for a local over-density consistent with the measured UHECR spectrum. With a 30% energy shift, each cosmic ray event in Auger’s correlation study would have an energy above 74 EeV instead of 57 EeV. GZK horizons
corresponding to $E_{\text{th}} = 74$ EeV then match well with the maximum valid distance of V-C catalog. Fittings to the shifted Auger spectrum indicate a possibility for the local over-density of UHECR sources.

We point out that the local over-density of UHECR sources is testable in the future cosmic ray astronomy where directions and distances of UHECR sources can be determined. Table IV shows percentages of cosmic ray events that come from sources within 30 Mpc for different values of $E_{\text{th}}$ and $n(l < 30 \text{Mpc})/n_0$. Although these percentages are calculated with $\gamma = 2.4$, $m = 3$ and $E_{\text{cut}} = 1000$ EeV, they are however not sensitive to these parameters. For $E_{\text{th}} = 57$ EeV and $n(l < 30 \text{Mpc})/n_0 = 1$, only 17% of cosmic ray events come from sources within 30 Mpc. For $n(l < 30 \text{Mpc})/n_0 = 2$ and the same $E_{\text{th}}$, 30% of cosmic ray events are originated from sources in the same region.

In conclusion, we have shown that the deviation of theoretically calculated GZK horizon to the maximum valid distance of V-C catalog can not be resolved by merely introducing the local over-density of UHECR sources. On the other hand, if Auger’s energy calibration indeed underestimates the UHECR energy, such a discrepancy can be reduced. More importantly, fittings to the shifted Auger spectrum indicate a possible local over-density of UHECR sources, which is testable in the future cosmic ray astronomy.

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| $n(l < 30 \text{Mpc})/n_0$ | $E_{\text{th}} = 57$ EeV | $E_{\text{th}} = 70$ EeV | $E_{\text{th}} = 80$ EeV | $E_{\text{th}} = 90$ EeV |
|--------------------------|-----------------|-----------------|-----------------|-----------------|
| 1                        | 0.17            | 0.27            | 0.36            | 0.46            |
| 2                        | 0.30            | 0.43            | 0.53            | 0.63            |
| 4                        | 0.46            | 0.60            | 0.70            | 0.77            |
| 10                       | 0.68            | 0.79            | 0.85            | 0.89            |

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