

An investigation of the cosmic rays above 1 EeV from the Cygnus region

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Abstract. The Cygnus region is a natural candidate of cosmic ray accelerator, with many OB associations, Wolf-Rayet stars and supernova remnants. Excesses of gamma and cosmic rays from the region were observed by several experiments, such as Milagro, AGASA and Fly's Eye. Using the stereo data of the HiRes experiment, the Cygnus region is studied in details. An excess of cosmic rays above 1EeV is observed with a significance of 4.1σ .

Keywords: UHECRs, anisotropy, Cygnus

I. INTRODUCTION

The origin of ultra-high energy cosmic rays (UHECRs) remains a mystery. One of the main aims of cosmic ray astronomy is to search for the anisotropy of UHECRs and to reveal the origin of Universe's charged particles with the highest energies. Cygnus Region is a natural candidate of cosmic ray accelerator. This region is the brightest region in Northern Hemisphere in both GeV and TeV regions. In addition to the large column density of matter, the Cygnus region contains 7 sources with gamma rays up to 100MeV detected by EGRET[1]. Milagro collaboration also reported that the region is the brightest area in their TeV gamma ray survey of Galactic plane[2]. This region is fairly young and contains a wealth of massive stars which grouped in 9 OB associations[3]. Especially Cyg OB2 association, it is the most massive stellar association known in our Milky Way and more like a young globular cluster like those observed in the Large Magellanic Cloud. It is only about 1.7kpc from us estimated to contain 2600 ± 400 OB type and 120 ± 20 O type stars. The total mass is about $10^5 M_{\odot}$ with the diameter about 60pc and the center mass density is about $40\sim 150 M_{\odot} \text{pc}^{-3}$ [4]. Besides the OB associations, there are more than 14 Wolf-Rayet (WR)[5] stars and many supernova remnants. All of these astrophysical objects may be the potential cosmic ray acceleration sites. Looking at the large scale structure of the galactic magnetic field, it is found that the field direction from the region is almost parallel to the line of sight[6]. The charged particles might suffer minor deflection, thus preserve somehow the source direction information.

There are also many interesting results about this region in historic UHECR experiments. The first result is reported by the Fly's Eye experiment which claims an excess with a chance probability of 6.5×10^{-4} in the direction of Cygnus X-3 with energy above 0.5EeV[7]. The analysis which chose Cygnus X-3 as a priori found

a maximal excess shifted towards higher galactic latitude (g.l.) at around 2° . Another result is from the AGASA collaboration who searched for large scale anisotropy of cosmic rays above 1EeV. Two regions, namely the center of our galaxy and the Cygnus region, stand out with 4.5σ and 3.9σ , respectively[8][9]. The maximum of excess around Cygnus region is located at about g.l. $\sim 5^{\circ}$, also shifted in the north in galactic coordinate. At totally different energy regime, around 1TeV, an excess in the similar direction is also reported as the Tibet AS_{γ} collaboration investigates the large scale anisotropy [10]. The excess is found smeared in a larger scale of approximately 20° in diameter. All of these observational facts hint that there might exist a nearby cosmic ray accelerator in the Cygnus direction and the galactic magnetic field may deflect the cosmic rays around 1EeV to slight higher g.l. and smeared the cosmic rays around 1TeV to a larger angular region. By putting all the hints together, we take a special direction $(l, b) = (75^{\circ}, 3^{\circ})$, as a priori, to be the geometrical center of the most dense area with local OB associations and WR stars which is around g.l. $= 1^{\circ}$ and slightly shift towards north in galactic coordinate. This reflects the fact observed in all high energy cosmic ray anisotropy measurements. Taking possible smearing into account due to the deflection, a relatively large window of $10^{\circ} \times 10^{\circ}$ is investigated. The local environment and the selected region are shown in Fig.1. In this paper the High Resolution Fly's Eye (HiRes) experimental data set has been analyzed for possible anisotropic excess of cosmic rays above 1 EeV in the very special Cygnus region.

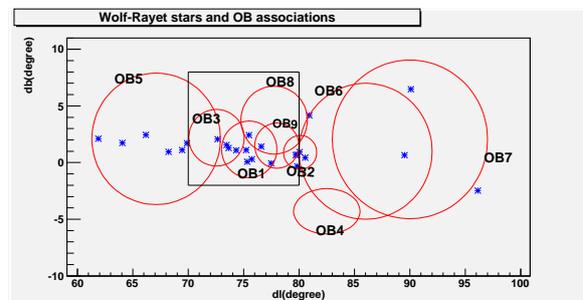


Fig. 1: The local environment of the Cygnus region, blue stars for WR stars, red circles for OB associations, the selected region is marked with a box.

II. THE HiRES EXPERIMENT AND THE DATA SET

HiRes is an experiment measuring air fluorescence light induced by air showers with two telescope arrays (HiRes-1 and HiRes-2) separated by 12.6km at Utah, USA (122° W longitude, 40° N latitude, vertical atmospheric depth 860g/cm²). With 22(42) telescopes at their sites, the HiRes-1(HiRes-2) detectors cover about 336°(360°) in azimuth direction and 3°-17°(3°-30°) in elevation[11], thus yield a field of view (FOV) in the Northern hemisphere from declination of -30° to 90°. The main advantage of the fluorescence technique is that the shower longitudinal development in the atmosphere is imaged and important quantities like shower size and height of shower maximum can be measured. The main shortcoming of the technique is low duty cycle about 10% and uneven exposure time due to different length of dark periods in nights of different seasons. HiRes-1 was operated from May 1997 while HiRes-2 started from December 1999. The two detectors can be operated independently. If a cosmic ray event triggers only one of the telescope arrays, it is called a monocular event. If the two telescope arrays are triggered by a common cosmic ray event, it is called a stereoscopic event. The arrival direction, then, is determined much more accurately than monocular ones. The aperture of the HiRes detector in the stereoscopic mode can be as large as 10⁴km²sr at 10²⁰eV.

Until April 2006 when the experiment terminated, approximately four million stereoscopic events had been recorded including artificial calibration events and noisy events. After reconstruction and quality cut, 9306 stereoscopic events above 1EeV are well measured with an angular resolution less than 0.53° and an energy resolution of 12%. The sky map of these events is shown in Fig.2.

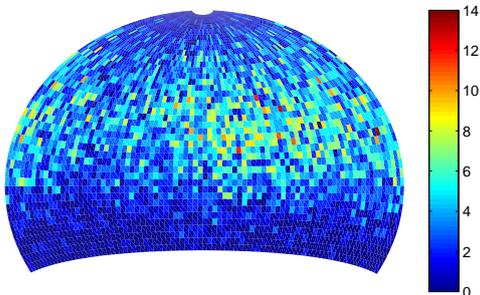


Fig. 2: The sky map of HiRes stereo data set in equatorial coordinate (right ascension α from right to left $[0, 2\pi]$, declination δ from -40° to 90°).

III. SHOWER DETECTION EFFICIENCY AND EXPOSURE TIME CORRECTION

The HiRes detector has different shower detection efficiency for showers entering the atmosphere with different zenith angles. In order to estimate background event rate for a given spot at declination δ and right ascension α in the sky, the first thing to do is correcting for the detection efficiency. Depending on when the observation is done, events from the given direction (α , δ) may come from totally different zenith angles in the local coordinate system. For a long period observation with relatively low event rate, an averaged efficiency over the whole experimental life time has to be used. Although the efficiency η is a very complicated function of energy E , impact-parameter R_p , zenith angle θ , azimuth angle φ , weather and atmospheric conditions and etc, it is easily obtained by simply counting the number of events in a cone with equal solid angle for each direction assuming cosmic rays arriving isotropically, i.e. the relative detection efficiency of the detector. The normalized detection efficiency by dividing with the total number of events is plotted in Fig.3 as a map of the local coordinates (θ , φ).

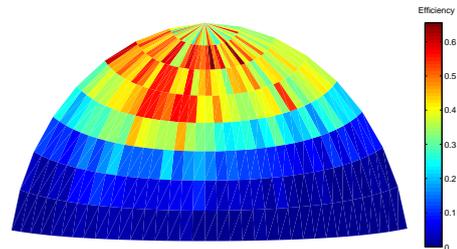


Fig. 3: The normalized detection efficiency map in the local coordinates (azimuth from right to left $[0, 2\pi]$, zenith from 0° to 90°).

Because HiRes telescope can only be operated in clear moonless nights, the total exposure time for a given spot (α , δ) in the life time of the experiment is modulated by seasons. This causes an uneven distribution of number of events in right ascension. Moreover, for spots that have same right ascension but different declinations, the exposure time is different as well because of the path length of those spots in the local coordinate system during the dark period. Therefore, a total exposure time for any spot in the sky, $\varepsilon(\alpha, \delta)$, ought to be calculated by integrating over the whole life time of the observation, namely,

$$\varepsilon(\alpha, \delta) = \int \eta(\theta(\alpha, \delta; t), \varphi(\alpha, \delta; t)) \chi(t) dt \quad (1)$$

where $\chi(t)$ is a step function that returns one when the spot (α , δ) is above the horizon else returns zero, $\eta(\theta, \varphi)$ is average detection efficiency read from the map in

Fig.3 and t is the detector on-time. The total exposure map as a function of (α, δ) , in unit of *hour* is shown in a Hammer-Aitoff projection, see Fig.4.

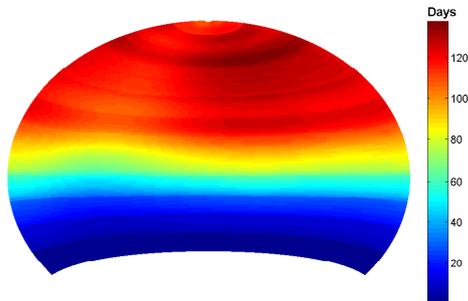


Fig. 4: The exposure, ϵ , distribution in equatorial coordinate (right ascension α from right to left $[0, 2\pi]$, declination δ from -40° to 90°).

IV. RESULTS AND AN INDEPENDENT CHECK

To estimate a significance of excess for a given spot, with a window of $10^\circ \times 10^\circ$, the background has to be estimated. In this analysis, the numbers of events in 8 surrounding windows which have same solid angle as the on-source window does are used as off-source ones. The Li-Ma formula[12] is used for the significance calculation. N_{on} and N_{off} refer to the numbers of events in the on-source and off-source windows, respectively and are directly counted from the data. The α factor is calculated by taking a ratio between the total exposure time of the on-source window and the sum of the total exposure time of all off-source windows. A distribution of the significance for every spot in the sky is plotted in Fig.5. Except for a window, the distribution fits a standard normal distribution well, with a width of 0.92 and a mean value of 0.04. The window, as a pre-decided prior including the Cygnus region, has 61 events in it, while the total number of events in the surrounding windows is 264 and the α factor is 0.124. An excess with 4.1σ from the direction of Cygnus region is found. The significance map for the local region is shown in Fig.5 with significance and number of events in each window.

Serving as a cross check to the exposure calculation, Right Ascension scanning method is used to re-analyze the data set. The points with the same declination have the same path when they pass through the local coordinate. So the detection efficiency is same for the points with the same declination. The efficiency correction is not needed and live time correction is enough for on-source and off-source windows. The declination band $34^\circ < \delta < 44^\circ$ has been chosen. In this declination band the R.A. range $294^\circ < \alpha < 314^\circ$ is chosen as on-source

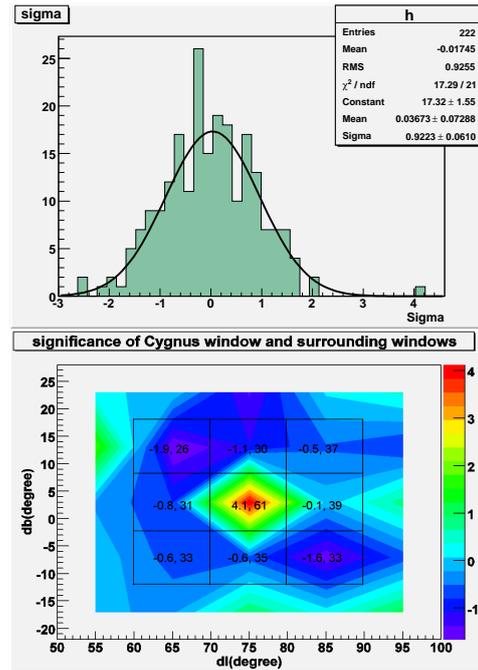


Fig. 5: The significance distribution of the whole HiRes sky (top) and the significance map around the Cygnus region. Squares represent the on-source window (center) and off-source windows (surrounding) with pairs of numbers that showing the significance and number of events in the windows (bottom).

window and the rest of this declination band as the off-source window. The hour angle is divided into 100 bins. The live time of the on-source and off-source windows in each hour angle bin is calculated in the whole observation period. By comparing live time ratio between on-source and off-source windows in each hour bin, the maximum ratio (0.1) is used as the α factor in the Li-Ma formula, thus the acquired significance is safe.

The number of events in on-source window is simply summed as N_{on} . The off-source events are binned according to the hour angle bin. The number of events in off-source windows and in each hour angle bin has been normalized to have the same on-time as in the on-source window and in the same hour angle bin. N_{off} , then, is a sum over all hour angle bins. Using Li-Ma formula, the significance for the window including Cygnus region is found to be consistent (3.8σ) in such a fast R.A. scanning analysis.

V. DISCUSSION AND SUMMARY

Two different methods of estimation for significance have been carried out with the stereoscopic data set and received almost same results. All the 61 events in the Cygnus window have been scanned one by one and all of them are good events. Arrival time of the 61 events is also investigated. Correlations between their directions and possible sources, such as massive stars, OB associations, are also checked.

The number of excess events over the background can be found using number of events in the on-source and off-source windows and corresponding α factor, namely

$$N^{excess} = N_{on} - \alpha N_{off} \quad (2)$$

The number of excess events is steadily increasing as observation goes on. There is no suspicious jump during the whole life time of the experiment.

The energy and X_{max} of the events in Cygnus Region have been compared with the whole data set as shown in Fig.6. Nothing that is abnormal is found. The energy distribution follows all others well. Energies of the events in the Cygnus region are mainly below 10EeV due to the statistics. Looking at the comparison between the X_{max} distributions for both "on-source" events and all others, one can not tell the difference of the two distribution. At first order approximation, the excess events are not photons or electrons that may yield different X_{max} distribution peaked at smaller depths than what is observed.

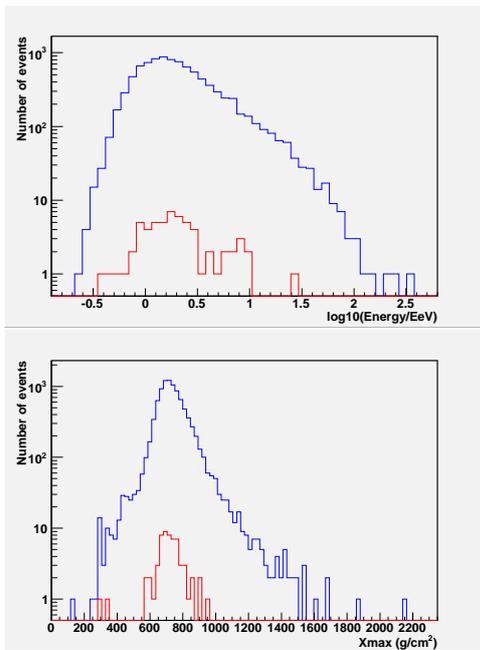


Fig. 6: The top plot is the energy (EeV) comparison between the whole data set and events in the Cygnus region and the bottom one is the X_{max} (g/cm²) comparison. The blue curve denotes the whole data set and the red one is for events in the Cygnus region.

If the excess of cosmic rays from the Cygnus direction was really associated with the OB associations and WR stars, the sources are very close to us, e.g. within 2kpc. The Galactic cosmic ray sources are considered to be supernova remnants (SNRs), however, the maximum energy achievable in acceleration by SNR shocks is believed not easily to be higher than 10¹⁵eV. On the other hand, stellar winds from massive stars are much better chance to be responsible. Stellar wind shocks are bounded on both sides by a highly turbulent medium

therefore short acceleration times are expected, and the shock velocity remains high significantly longer than for shock waves of SNRs[13]. The OB associations and WRs seem to be more attractive. All OB associations and WRs are plotted together with arrival directions of events in the window as shown in Fig.7. There is no direct correlation between them. One obvious reason is that those events in the window must be deflected by the magnetic field on their way to the Earth. Unfortunately, at a scale of 1~2kpc, there is no reliable knowledge about the field, especially for turbulence at all scales.

It is interesting to observe a fact that all experiments terminated their operation at such a moment that the excess reached to 4 σ , so that none can confirm the existence of the source concretely. A more dedicated experiment is demanded.

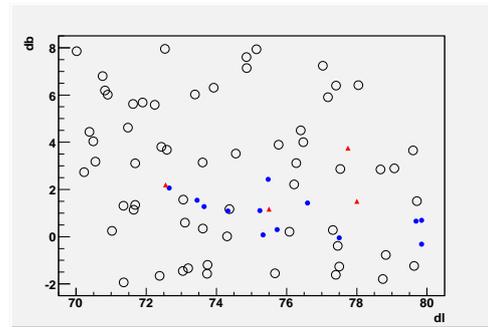


Fig. 7: Map of HiRes events (black circles), OB associations (red triangles) and WRs (blue dots) in the selected window.

VI. ACKNOWLEDGEMENT

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