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THE HIGHEST ENERGY COSMIC RAY*

F. HALZEN and R.A. VÁZQUEZ

Department of Physics, University of Wisconsin, Madison, WI 53706, USA

T. STANEV and H.P. VANKOV

Bartol Research Institute, University of Delaware, Newark, Delaware 19716, USA

ABSTRACT

One should keep in mind that the highest energy cosmic rays may be photons or neutrinos. We discuss the particle assignment of the 3×10^{20} eV shower recently observed by the Fly's Eye detector. We show that the event is not initiated by a photon and that the assignments of a proton and neutrino as the primary particle are, arguably, equally valid. Neither assignment is totally satisfactory.

1 Introduction

In October 1991, the Fly's Eye experiment recorded an event of energy $3.0 \pm_{0.54}^{0.36} \times 10^{20}$ eV [1]. This event, together with the event recorded at the Yakutsk experiment on May 1989 [2], of estimated energy $\sim 2 \times 10^{20}$ eV, constitute the two highest energy cosmic rays ever seen. Their energy corresponds to a center of mass energy of the order of 700 TeV or ~ 50 Joules, almost 50 times LHC energy. Most remarkably, the arrival directions of the two events coincide, within angular resolution, possibly indicating a common origin. There is, however, no obvious candidate source in that region of the sky. The parameters of both events are listed in Table 1. The measured Fly's Eye spectrum is shown in Fig. 1. Note that the highest energy event does not fit onto the continuation of the spectrum measured at lower energy.

Table 1: Characteristics of the two highest energy events. α and δ is the arrival direction in celestial coordinates.

Event	Energy (10^{20} eV)	Flux ($\text{cm}^2 \text{ s sr}^{-1}$)	α	δ
Fly's Eye	$3.0 \pm_{0.54}^{0.36}$	7.4×10^{-41}	$86^\circ \pm 1^\circ$	44°
Yakutsk	$1.2 - 2.3$	1.9×10^{-36}	$75^\circ \pm 10^\circ$	$45^\circ \pm 4^\circ$

The highest energy cosmic rays are almost certainly extragalactic. A high energy spectral cutoff in the vicinity of 10^{20} eV is anticipated as a consequence of their interaction with cosmic photons. Beyond this cutoff high energy γ -rays and neutrinos are predicted to dominate the spectrum [3]. It is therefore not unreasonable to question

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Fig. 2: The composite atmospheric shower profile of a 3×10^{20} eV γ -ray shower calculated with Bethe-Heitler (solid) and LPM (dash) electromagnetic cross sections. The central line shows the average shower profile and the upper and lower lines show 1σ deviations --- not visible for the BH case, where lines overlap. The experimental shower profile is shown with the data points.

The observed shower profile roughly fits that of a proton. It is interesting to notice that a heavy nucleus interpretation cannot be excluded. Heavier nuclei have a lower average $x_{\max}$, typically 700 gr cm^{-2} , the exact value depending on the mass of the nucleus. A medium mass nucleus, say O or C, would fit quite well the detected shower profile. The fluctuations in $x_{\max}$ of proton showers are quite large and a proton origin cannot be excluded from the observed shape of the shower profile.

The shower profile information is sufficient to conclude that the event is unlikely to be of photon origin. Photons of this energy interact in the geomagnetic field, thus starting a cascade well before entering the atmosphere [6, 7, 8]. We carried out a Monte Carlo simulation of the atmospheric shower profile, which included interactions with both the Earth's magnetic field and the atmosphere. Cross sections necessary for the computation of the cascade on the magnetic field were taken from Erber [9]. A 10^{20} eV photon encountering the ever increasing geomagnetic field will interact somewhere between 500 and 10000 km above the Earth's surface. The most probable height is 3000 km. The dipole magnetic field at that distance is roughly 0.1 Gauss. Notice that the shower direction in this event is almost perpendicular to the field lines. In the primary interaction the photon is transformed into an pair of electrons. This subsequently suffer energy loss as a result of magnetic bremsstrahlung, which

is peaked forward, $h\nu/E$ peaks at ~ 0.1 for $E = 10^{20}$ eV and $H = 0.1$ Gauss. The photon shower created on the geomagnetic field consists on average of 6 γ -rays carrying 65% of the primary energy. These γ -rays of energy above 10^{19} eV will initiate the development of the atmospheric cascade. After further cascading the overall photon energy distribution peaks at 10^{17} . One must take into account that at such energies the electromagnetic cascade is slowed down by the LPM effect [8]. In Fig. 2 we show the shower profile of 3×10^{20} eV γ -ray shower in the geomagnetic field and the atmosphere calculating with and without the LPM effect. The detected shower has an $x_{\max} = 815 \pm_{35}^{45}$ gr cm $^{-2}$. Without the LPM effect (Bethe-Heitler cross section) the γ -ray shower peaks at 900 gr cm $^{-2}$. Inclusion of the LPM effect increases the depth of shower max by 100 gr cm $^{-2}$. As a result of the large number of secondary photons that contribute to the composite air shower, the fluctuations are very small. In Fig. 2 we actually show the 1σ fluctuation for 100 simulated showers. A shower from the same primary photon would have reached maximum at 1075 gr cm $^{-2}$ in the absence of the geomagnetic field. We conclude that the hypothesis of the event being a γ -ray is not consistent with the experimental observations. The same conclusion is likely for the Yakutsk event which is recorded by a giant array of 18 km 2 . The detector consists of scintillators, Čerenkov detectors, muon detectors and antennas for radio frequency detection. The measured density profile shows a huge number of muons which also questions a γ -ray origin.

Neutrino origin is consistent with the observed profile. A neutrino interacting high in the atmosphere transfers roughly half of its energy to an air nucleus which subsequently produce a hadron-like cascade. Such events must, of course, be atypical since one expects a weakly interacting particle to interact at much greater depth. We must, however, consider the possibility that at these energies, where the atmosphere is still transparent to neutrinos, we are observing neutrinos in the tail of a distribution that reaches its maximum inside the Earth.[†]

3 Origin and Propagation

The shower development of the Fly's Eye event and the density of muons of the Yakutsk experiment lead to the conclusion that both are either protons, nuclei, or maybe neutrinos. These interpretation are not without further problems. The mean free path $\lambda_{p\gamma}$ of a 3×10^{20} eV proton on the cosmic photon background is 8.8 Mpc, see Fig. 3. $\lambda_{p\gamma}$ reaches a minimum of 3.6 Mpc at $E_p = 1.5 \times 10^{21}$ eV and is approximately constant at higher energy. This estimate is very reliable, since the main contribution to the photon target is from the microwave background.

We have propagated 3×10^{20} eV protons through the 3 K background to establish the relation between proton energy at the source and the source distance. Protons

[†]Notice that we would not necessarily expect more events deeper in the atmosphere since one has to take into account that the reconstruction efficiency and the effective volume decreases with the zenith angle making it more difficult to see such events.

Fig. 3: Mean free path (Mpc) for interaction of protons and γ -rays on the isotropic photon background as a function of the energy (eV). The background spectrum includes the microwave and radio backgrounds. The γ -ray interaction length in the absence of radio background is shown with a dotted line.

interacting exactly at $1 \lambda_{p\gamma}$ lose, on average, 20 % of their energy. A cosmic ray proton needs an energy of 3×10^{22} eV to arrive at Earth from a 100 Mpc source with the observed energy. A source energy of 10^{25} eV is required for a distance of 276 Mpc. In this case the proton would undergo 47 collisions on the microwave background. Alternatively, the probability for a proton to traverse 100 Mpc without an interaction is 1.16×10^{-5} . For 276 Mpc this number is reduced to 2.4×10^{-14} .

The calculation of $\lambda_{\gamma\gamma}$ is more uncertain since the cosmic background radio may contribute to the photon target. We calculated $\lambda_{\gamma\gamma}$ using an estimate of the isotropic radio background by Berezhinsky [10] which is fully consistent with recent measurements [11]. $\lambda_{\gamma\gamma}$ at 3×10^{20} eV is 21 Mpc. For a radio background twice as large as estimated by Berezhinsky, $\lambda_{\gamma\gamma}$ would be 13 Mpc, and 40 Mpc for one half the same estimation. In Fig. 3 we also show the mean free path for photons as a function of the energy.

No nearby candidate sources exists within the resolution of the observed arrival direction. Charged particles travelling in intergalactic space with energies of the

order of 10^{20} eV are not significantly deflected by the intergalactic magnetic field which is very small. Also their gyroradius in the galaxy exceeds its dimensions. After travelling a distance of 30 Mpc in a magnetic field of 10^{-8} G the deflection would be at most 10° [4].

4 Energetics

The event recorded on October 1991 implies a differential flux of [1]

$$\frac{dN_p}{dE} = 7.4 \cdot 10^{-41} (\text{cm}^2 \text{s} \text{eV})^{-1}, \quad (1)$$

at $E = E_{\text{max}}$. If we assume that the initial particle was a neutrino we have to scale the flux according to the interaction cross sections, *i.e.*:

$$\frac{dN_\nu}{dE} = \frac{\sigma_p(E_{\text{max}})}{\sigma_\nu(E_{\text{max}})} \frac{dN_p}{dE}, \quad (2)$$

where σ_p, σ_ν are respectively the proton-air, neutrino-air cross section at the energy of the event. Let's define

$$\alpha = \frac{\sigma_p(E_{\text{max}})}{\sigma_\nu(E_{\text{max}})}. \quad (3)$$

In the absence of new physics $\alpha \sim 10^6$ and the particle physics is sufficiently precise to bracket its value in the range $\alpha \sim 10^5 - 10^7$. Such a flux can be understood as the flux produced by an extragalactic source at a distance of $d \sim 10^2$ Mpc with a neutrino luminosity of the order of $\mathcal{L} = 10^{45} \sim 10^{50} \text{ erg s}^{-1}$. This are totally acceptable values e.g. for the emission of particles during the high state of a AGN jet beaming, possibly, in our direction.

Using the values for the flux quoted above and assuming a flux of the form $dN/dE = aE^{-\gamma-1}$, we get

$$\mathcal{L} \simeq 1.3 \times 10^{44} \alpha \text{ erg s}^{-1} \quad \text{for } \gamma = 1, \quad (4)$$

$$\mathcal{L} \simeq 1.3 \times 10^{43} \alpha \text{ erg s}^{-1} \quad \text{for } \gamma = 0, \quad (5)$$

for $d = 100$ Mpc. For the range of expected values of α we get a luminosity in the range of AGN luminosities.

For acceleration in AGN jets $\gamma = 0$ near E_{max} [12]. We may have underestimated the luminosity as the neutrino energy is, on average, a fraction of the energy of the protons initiating the proton cascade in which the neutrino originated. We, on the other hand, neglected the effect of beaming of the jet which could reduce the estimated luminosity by a factor 10^3 [13]. Given the 2 orders of magnitude uncertainty in the flux estimate the luminosity could be as low as $10^{45} \text{ erg s}^{-1}$ for a 100 Mpc source.

It is not clear that one should detect a low energy neutrino flux associated with this event because of the reduced detection efficiency for detecting lower energy neutrinos

and the expectation of a very hard spectrum peaking near the maximum energy. It is an experimental fact that the observed luminosity of objects such as 3C279 peak at high energy. This is likely to be more so for neutrinos as the highest energy photons are likely to be absorbed in the source and are therefore not observable. Their neutrino counterparts will be detected. Also, the neutrino assumption “explains” why the event does not seem to fit the high energy proton spectrum. The origin of the neutrino could be a “hidden source” with no counterpart in other high energy radiation.

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