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Legacy from Fly’s Eye: Making sense of the highest energy cosmic ray ever observed

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The Fly’s Eye detector recorded the most energetic cosmic ray event ever observed. With an energy of 320 EeV, it lays far beyond the suppression of the ultra-high energy cosmic ray (UHECR) energy spectrum. If its energy is indeed well determined, as the data strongly suggests, then it remains either a great mystery or an unbelievable chance, given the very small exposure of Fly’s Eye when compared to those of subsequent observatories, which have never observed a remotely comparable event. At energies as high as those of the Fly’s Eye event, the Universe is very opaque to electromagnetic interacting particles, whether protons or heavy nuclei, and therefore its source must be relatively close. Using numerical simulations for the propagations of protons and nuclei, we reexamine different hypothesis about the nature and location of the source both for the full-sky spectrum observed by Telescope Arrayonly and with a superimposed secondary component which only becomes dominant at energies beyond 100 EeV. We show that the latter scenario, inducing a hardening of the spectrum at the highest energies, is more likely to reconcile the fact that Fly’s Eye was able to observe such event but no particles at lower energies (e.g., at 100 EeV) while still being compatible with the non-observation of equivalent events by neither HiRes or Telescope Array, with higher exposure in the Northern Hemisphere.

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1. Introduction

Detected in 1991, the Fly's Eye event is a challenge for science since this is the highest energy cosmic ray ever observed with an energy of 320^{+92}_{-94} EeV [1]. The clear fluorescence profile make the detection hardly contestable. Then this event lies far beyond the GZK cut-off. Indeed a proton would have interact with photons from the cosmological microwave background through photo-pion production [2, 3]. It is even worse for a heavy nuclei that would have been absorbed through photo-desintegration on background photons (infra-red or cosmological microwave background) on a shorter distance [4].

All studies lead until now, by computing the depth of the shower maximum X_{max}, were enable to precisely determined the nature of this particle. Recent results favours a proton or a heavy nuclei (C, Fe) but a photon is not completely excluded neither [1, 5, 6].

The Fly's Eye event's arrival direction is quiet well-determined [right ascension: $85.2^\circ \pm 0.48^\circ$, declination: $48^\circ \pm 6^\circ$, galactic latitude: 9.6° , galactic longitude: 163.4°, 1]. Deflection of cosmic rays in the intergalactic medium is hard to constraint because the Extragalactic Magnetic Field is poorly know [see, e.g., 7, for a review]. Even for a such high energy particle as the Fly's Eye event, the effect is important. Moreover to identify the source, the method consists in backtracking the particle and neglects the interactions. This procedure is dependent on both the nature of the particle and the maximum distance of the source. Both informations are unknown thus recent results were only able to suggest possible sources but not identifying it clearly. Quasars and AGNs as well as cataclysmic events such as gamma-ray burst, birth of millisecond pulsars or magnetar flares can be potential sources [8–11].

Then three decades later, the event remains unexplained while, as far as we know, no one ever published a strong argument against the reality of the observation. In the same time, none of the more recent observatories (HiRes, Telescope Array or Pierre Auger Observatory) ever observed another event like this. This is even more puzzling.

In this work, we evaluate the likelyhood that Fly's Eye can indeed observe such an event while Telescope Array can not. We start with a simple model of the cosmic ray spectrum given by the sky seen by Telescope Array and adding a secondary component (Sec. 2). Then in a second time, we have tested the impact the propagation of both iron nuclei (Sec. 3) and protons (Sec. 4) with numerical simulations.

2. A simple cosmic rays spectrum model

To start this inquiry, lets consider the all-sky spectrum fitted with Telescope Array [12]:

$$J_{TA}(E) \propto \begin{cases} E^{-\gamma_1}\,, & E < E_{\text{ankle}}\,, \\ E^{-\gamma_2}\,, & E_{\text{ankle}} < E < E_{\text{break}}\,, \\ E^{-\gamma_3}\,, & E > E_{\text{break}}\,, \end{cases} \tag{2.1}$$

where $E_{\text{ankle}} = 5.2 \pm 0.2$ EeV, $E_{\text{break}} = 60 \pm 7$ EeV, $\gamma_1 = 3.226 \pm 0.007$, $\gamma_2 = 2.66 \pm 0.02$ and $\gamma_3 = 4.7 \pm 0.6$.

The result is converted in number of events observed per energy bin and plotted on figure 1 (left, red dashed line). As a matter of comparison, the number of events observed by Pierre Auger

Observatory (red stars) and Telescope Array (blue dots) are also plotted. Assuming that Telescope Array and Fly's Eye see the same sky, the spectrum given by the equation 2.1 should also describe the number of events seen by Fly's Eye but with a lower exposure [$\sim$ 5000 km^2.yr.sr against 8300 km^2.yr.sr, 13–15]. This extrapolation is plotted on figure 1 (left, orange dashed line). One can see that the probability of observing 1 event with Fly's Eye is below $\sim 5 \times 10^{-3}$.

Considering that Telescope Array had not observed a single event at this energy, it argues for a fluke. Either the particle has travelled mean free path without or with few interactions. If it can not be totally rule-out, it does not explain why no counterpart at lower energy have not been seen. Indeed, at the Fly's Eye energy both for protons and iron nuclei, the mean free path increase quickly with the energy decreasing. Or the Fly's Eye event has been emitted by a local source allowing Fly's Eye to see an event and not Telescope Array. In this case, this source shall be transient otherwise counterpart in X-ray and gamma for instance shall have been observed. Then the burst occurs long time ago and only charged particles which has travelled a longer time due to magnetic deflection are now detected.

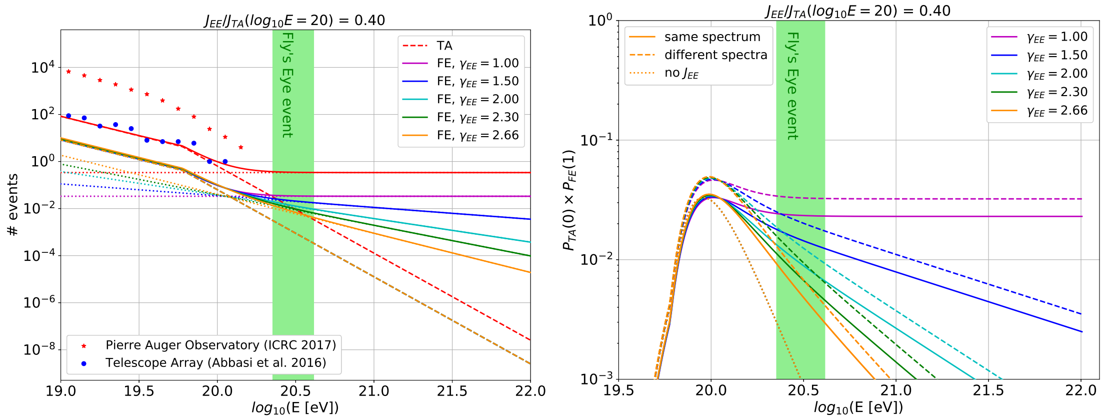

Figure 1: Left: Number of events predicted by the Telescope Array spectrum for Telescope Array and Fly's Eye (red and orange dashed lines respectively). Secondary component for different powerlaw indexes γ_{EE} (dotted lines): in red $\gamma_{EE} = 1$ for Telescope Array, in other colors for Fly's Eye. Both spectra cumulated in plain lines. **Right:** Poissonian probability that Fly's Eye see one event ($P_{FE}(1)$) while Telescope Array see none ($P_{TA}(0)$) versus the energy considering that both see the same spectrum ($J_{TA} + J_{EE}$) in plain lines and that only Fly's Eye saw the extremely high energy component (J_{EE}) for different powerlaw index γ_{EE} (colors).

To model, this second potential source, we add a second hard spectrum component:

$$J_{EE}(E) \propto E^{-\gamma_{EE}}. \tag{2.2}$$

This secondary component is normalize so that the total spectrum ($J_{TA} + J_{EE}$) does not violate the Telescope Array observations. This condition is fulfilled for $J_{EE}/J_{TA} < 0.5$. We represent this secondary component for different powerlaw spectra (γ_{EE} =1, 1.5, 2, 2.3, 2.66) on figure 1 (left, dotted lines). The red dotted line is normalized for Telescope Array with $\gamma = 1$. Combined spectra are plotted in solid lines.

From these numbers of events predicted, we can compute the probability to not detect a single event with Telescope Array ($P_{TA}(0)$) and detect one with Fly's Eye ($P_{FE}(1)$). The combined probability ($P_{FE}(1) \times P_{TA}(0)$) is plotted on figure 1 (right) for three cases: without a secondary component (dotted line), with a secondary component seen only by Fly's Eye (unrealistic control scenario, dashed lines), with a secondary component seen by both observatories (solid lines). Without secondary component, there is only a peak at 10^{20} eV while with a hard secondary spectrum ($\gamma < 1.5$) the probability is flat at higher energy. This argues for a hard secondary spectra but this results missed the propagation that changes the conclusion. We will study this in the two next sections.

3. Case: Fly's Eye is a heavy nuclei

The propagation depends on the type of primary particle injected. According to the last results from Pierre Auger Observatory [16] and which are compatible with the results from Telescope Array [17, 18], ultra-high energy cosmic rays should heavy nuclei (heavier than ^{14}N).

Lets start by studying the case where the Fly's Eye event was emitted as an iron (^{56}Fe) and lose its energy and nucleons through photo-disintegration. Using CRPropa 3 [19] in a 1D mode, we propagated 10^5 iron nuclei for each source energy without taking into account the cosmological effects. Photo-disintegration is computed both on Cosmological Microwave Background and Infra-Red Background photons [using model presented in 20]. On figure 2 (left) is represented the evolution of the mass number versus the distance traveled of an iron emitted at 250 EeV (purple), 320 EeV (blue), 500 EeV (yellow) and 800 EeV (red) while it is loosing nucleons through photo-disintegration. The 68% and 95% confidence level areas are also plotted to exhibit the fluctuations. The iso-energy lines of 100 , 226 (lower limit of the Fly's Eye event), 320 and 442 EeV (upper limit of the Fly's Eye event) are added.

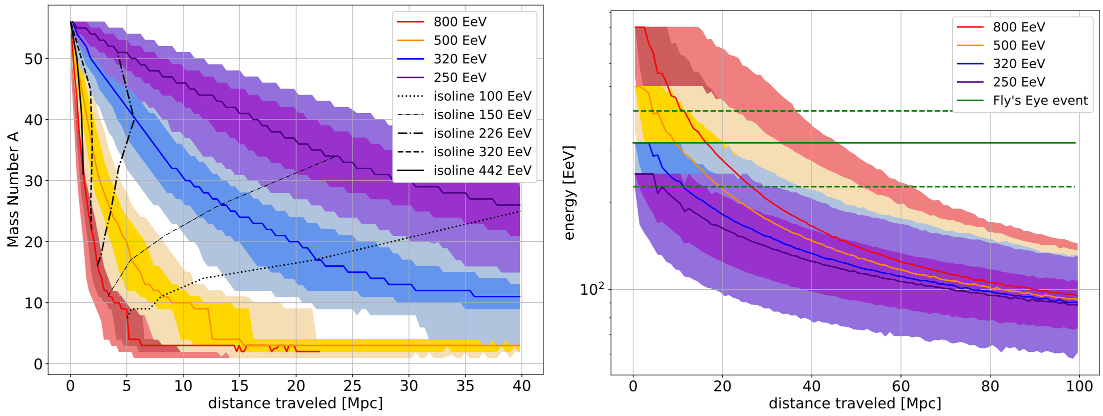

Figure 2: Left: Evolution of the mass number of nuclei due to photo-disintegration considering initial iron nuclei with energies of 250 EeV (mauve), 320 EeV (blue), 500 EeV (yellow) and 800 EeV (red) versus the cosmological distance traveled ($D_{travel} = c \cdot t$ where t is the cosmological time). Median value in plain line, 68% and 95% confidence level are plotted respectively in bold and light color area. Isolines show where the particle reaches 100 (dots), 226 (lower limit of the Fly's Eye event, dots-dashes) and 320 (dashes) EeV. **Right:** Same but evolution of the energy of protons interaction through photo-pion production.

Interestingly, by injecting iron nuclei with energy higher than 320 EeV, they lose masses extremely fast and are below ^{14}N in less than few Mpc. Moreover, the isoline 320 EeV is vertical at

$2-3$ Mpc. Which means that a whatever is the initial energy injected, the nuclei will reach the energy of the Fly's Eye event after few Mpc. Then a source located at this distance should increase the probability of detecting a Fly's Eye event.

To test, this hypothesis, we have run a new set of simulations with CRPropa 3 [19]. This time we have used a 3D mode without magnetic field and with a magnetic field of 1 nG and 1 Mpc coherence length. These are the extreme values that we can expect for the Extragalactic Magnetic Field. The galactic magnetic field has not been take into account because at this energy it will barely deflect the particle and because the Fly's Eye is almost located at the anti-galactic center. To reduce the computation time and increase the number of observed events, we have placed the source emitting isotropically at the center of a sphere of radius the distance to the source. All the events reaching the source are recorded. The simulation is run over 200000 initials iron nuclei following a powerlaw injection spectrum between 10^{19} eV and 10^{22} eV. One simulation is done per set of parameters of distance (D_s), powerlaw index and magnetic field (0 or 1 nG).

The results of one simulation ($D_s = 2$ Mpc) is plotted on figure 3 (top, left). The events pill-up at the exact energy of the Fly's Eye event (320 EeV). Moreover injecting a really hard spectrum ($\gamma_{EE} = 1$) create a specific pattern where there are a valley at 100 EeV and a peak at 320 EeV which reproduce exactly the results of Fly's Eye. From the results of simulation we can recompute the Poissonian probability for each γ_{EE}. The result is plotted on figure 3 (bottom, left). A second peak appears at $\log E = 20.5$. If Telescope Array and Fly's Eye see the same sky, the probability of observing an event like the Fly's Eye event is about $\sim 15\%$.

4. Case: Fly's Eye is proton

The analysis made in section 3 has been remade but by injecting proton instead of iron nuclei. On figure 2 (right) is represented the energy of a proton versus the distance traveled interacting through photo-pion production. The energy limits of the Fly's Eye event are also plotted. Contrary to iron, there is no specific pattern arising. Increasing the initial energy of the proton will increase the distance at which the Fly's Eye event energy is reached (fluctuations included). In particular, we can not extract a specific distance that allow to drastically increase the number of event at 320 EeV to make detectable by Fly's Eye without detecting any at 100 EeV due to a too low sensitivity.

In the best case, a hard spectrum injected ($\gamma_{EE} = 1$) allows create a peak of events but only around $10^{20.1}$ (figure 3 top, right). This excess is even more clear if we compute the Poissonian probability (figure 3 bottom, right). It highlights that, in the case of a secondary component composed of proton, it is more probable to detect an event at 10^{20} eV with Fly's Eye at $10^{20.5}$ eV. Then a Fly's Eye emitted as a proton seems less probable. Playing on the distance of the source or the cut-off energy does not change its position in the spectrum only its size.

5. Conclusion

We have shown that the spectrum fitting the Telescope Array data can not explain only the Fly's Eye event. A secondary component with a hard spectrum ($\gamma_{EE} \sim 1$) is necessary. But this secondary spectrum alone does not explain why the Fly's Eye event has been detected specifically

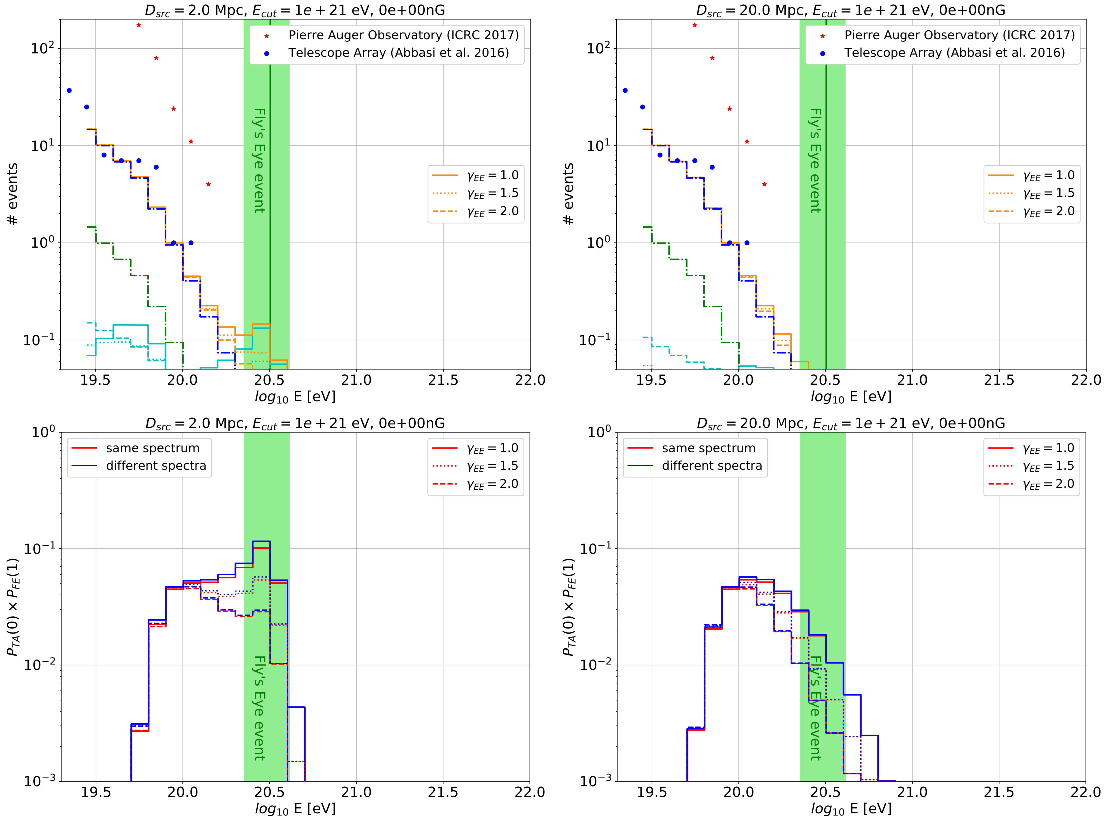

Figure 3: Top: Predicted spectrum for Telescope Array and Fly's Eye (respectively blue and green dotted dashed lines). Spectra in number of particles for a source at 2 Mpc injected iron nuclei following a powerlaw spectrum of index γ_{EE} and cutting at $E_{cut} = 10^{21}$eV (cyan curves). Results are normalized so that the number of events of the Telescope Array predicted spectrum plus the simulated one does not exceed 1 at 10^{20}eV. Cumulative spectra with the predicted Telescope Array are put in orange. Data point for Pierre Auger Observatory, Telescope Array and Fly's Eye and the limits of the Fly's Eye event are also plotted. **Bottom:** Poissonian probability that Fly's Eye see one event ($P_{FE}(1)$) while Telescope Array see none ($P_{TA}(0)$) versus the energy considering that both see the same spectrum ($J_{TA} + J_{EE}$) in plain lines and that only Fly's Eye saw the extremely high energy component (J_{EE}) for different powerlaw index γ_{EE} simulated (colors). **Left:** iron nuclei injected at 2 Mpc, **right:** proton injected at 20 Mpc.

at this energy. To improve the simple model, we have study the case of the propagation of iron nuclei and protons.

In particular, we have shown that iron nuclei injected with an energy higher than 320 Eev tend to reach this energy after travelling a distance of 2 to 3 Mpc. The consequence is that a source located at this distance will generate an observed spectrum with an excess of events at 320 EeV and a deficit at 100 EeV. A such a short distance, if it is a steady source we should see it in every wavelength. Then this result argues for a bursting source located at ~ 2 to 3 Mpc. This gives a strong explanation to the results of Fly's Eye and in particular why with a lower exposure, it manages to observed an event at such high energy while any other experiment failed. Moreover we have shown that to conciliate the results from Fly's Eye and Telescope Array, we need a source injecting with a hard spectrum ($\gamma_{EE} = 1$) and low cut-off energy (10^{21} eV). This is in agreement with other recent results [21, 22].

The same analysis lead on proton injection failed to give a explanation. Never the less, the possibility of a secondary component of protons with a hard spectrum extending at higher energy can not be completely ruled out. But this picture is more complicate to draw as far as the production of neutrino and gamma-rays will be important and can exceed the limits already put on the neutrino and gamma-ray background [22, 23, and references inside].

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