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A doublet of cosmic-ray events with primary energies $> 10^{20}$ eV

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The Telescope Array Collaboration has observed a cosmic-ray event with estimated primary energy of $1.38 \cdot 10^{20}$ eV whose arrival direction coincides [T. Abu-Zayyad et al. (Telescope Array Collaboration), arXiv:1205.5984], given the angular resolution of 1.5°, with that of an event with estimated primary energy of $1.23 \cdot 10^{20}$ eV observed by the Pierre Auger Observatory. The total number of events with energies $> 10^{20}$ eV published by both experiments is six. I estimate the statistical significance of the doublet, which is rather weak, and point out that the arrival directions of events in the doublet coincide with the Galactic X-ray source Aql X-1.

Despite decades of intense studies, including those by recent huge experiments, sources of ultra-high-energy cosmic rays (UHECRs) remain unknown. For the primary cosmic-ray particles with energies of order 10^{20} eV or higher, quite simple astrophysical arguments restrict the number of potential accelerating astrophysical sources drastically [1, 2]. At the same time, the Greizen [3], Zatsepin and Kuzmin [4] (GZK) effect shortens the mean free path of protons and nuclei with those high energies considerably, putting an additional constraint that sources of these events should be nearby. This logic has been supported by the recent observations of the flux suppression at high energies consistent with the GZK predictions by the High-Resolution Fly's Eye (HiRes) [5], Pierre Auger Observatory (PAO) [6] and Telescope Array (TA) [7] experiments. The observation of the suppression does not mean however that no "super-GZK" events are observed. Two largest and most modern arrays of surface detectors have published coordinates of three events each [8, 9] with energies $E > 10^{20}$ eV. It is these six events which will be primarily concerned in this note.

For the "sub-GZK" ($E \sim 6 \cdot 10^{19}$ eV) events, early PAO data suggested a weak correlation of cosmic-ray arrival directions with positions of nearby active galactic nuclei (AGN) [10] which might be interpreted as an indication to acceleration of UHECRs in these astrophysical objects. This interpretation has been criticised on the basis of numerous arguments, see e.g. [11–13]; it has not been supported by the data of HiRes [14] and TA [9] though it has been supported by the Yakutsk data [15]. A subsequent publication of the Pierre Auger collaboration [8], based on enlarged statistics, demonstrated a much weaker effect. However, the highest-energy events with $E > 10^{20}$ eV did not correlate with AGN even in the data set with the strongest signal.

As it has been pointed out in recent Ref. [9], where coordinates of TA events have been made public for the first time, the arrival direction of one TA event with $E > 10^{20}$ eV coincides, within the experimental precision, with that of a PAO event of the similar energy. Details of the two events are given in Table for convenience. The sky map with all six events with $E > 10^{20}$ eV is presented in Fig. 1. The appearence of the doublet is psychologically surprising because the two experiments are located in different hemispheres and see different parts of the sky with a moderate overlap in the equato-

Details of the two events with coinciding arrival directions: the experiment name; date; energy in units of EeV $= 10^{18}$ eV; equatorial coordinates

Exp.	Date	E, EeV	RA	DEC
PAO	09.10.2008	123	287.7°	+1.4°
TA	28.02.2011	138	288.5°	−0.0°

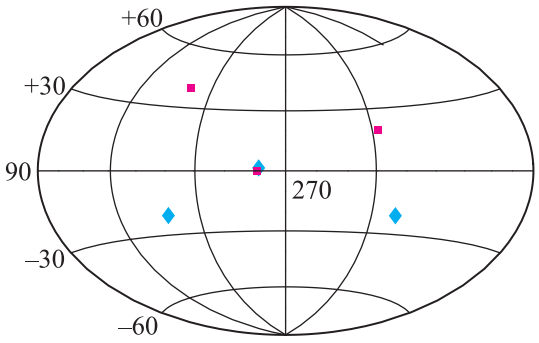

Fig. 1. The sky map with arrival directions of three PAO events with $E > 10^{20}$ eV (diamonds) and three TA events with $E > 10^{20}$ eV (boxes). The Hammer projection, equatorial coordinates

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rial region. The zoom of the skymap, with error circles of events, is presented in Fig. 2.

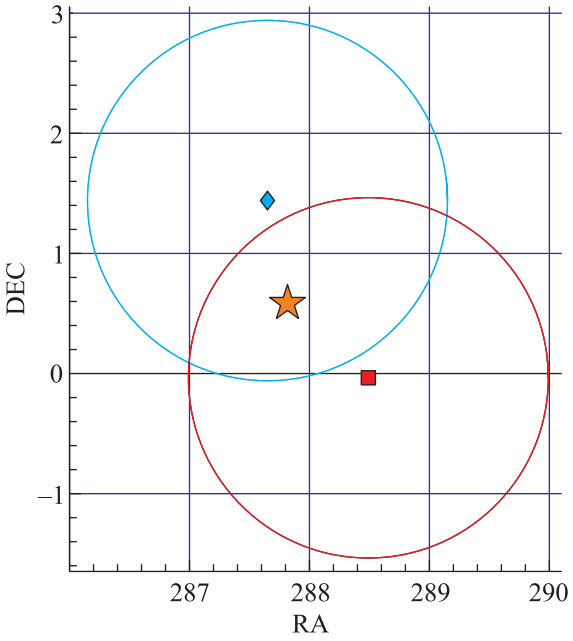

Fig. 2. The sky map with arrival directions of the two events in the doublet: the PAO event (diamond) and the TA event (box). With a 68% probability, the true arrival directions are inside the corresponding circles. The star denotes the position of Aql X-1; no other strong X-ray or gamma-ray sources are seen nearby

To estimate the statistical significance of this doublet we follow the usual procedure described in Ref. [16] (see also [17, 18]). We assume the isotropic distribution of arrival directions, account for direction-dependent experimental exposure and simulate a sufficient number of Monte-Carlo sets of events, then count how often the same or larger number of doublets happens as a fluctuation of the isotropic distribution. For this purpose, a doublet is defined as a pair of arrival directions separated by not more that $\sqrt{2}\theta_0$ where the angular resolution $\theta_0 \approx 1.5^\circ$ for both PAO and TA.

For three PAO and three TA events ($E > 10^{20}$ eV), the P-value calculated in this way is $P \approx 3.7 \cdot 10^{-3}$. This value may be interpreted as an estimate of the probability to have one doublet anywhere in the combined data set as a fluctuation of the isotropic distribution of arrival directions. However, this interpretation should be taken with care because the choice of the energy threshold, 10^{20} eV, is somewhat arbitrary.

We see that the statistical significance of the doublet is not that impressive. Many three-sigma effects have come and gone in cosmic-ray physics. Nevertheless, it is tempting to speculate about the potential source of the particles. The region of interest is located close to the Galactic plane, in the zone of avoidance where not many extragalactic objects are identified. However, strong active galaxies which might accelerate particles up to ultra-high energies are expected to be X-ray and/or gamma-ray sources visible through the dust obscuration at this location (Galactic coordinates of the center of the doublet are $l \approx 35.9^\circ$, $b \approx -4.3^\circ$). In representative catalogs of active galactic nuclei (Veron-Cetti and Veron [19]), gamma-ray sources (2FGL [20]) and X-ray sources (ROSAT bright source catalog [21]), there is only one bright source within a few degrees of this location, a low-mass X-ray binary star Aql X-1, just in the middle of the doublet (see Fig. 2). There are no active galaxies nor other identified ROSAT X-ray or FERMI-LAT gamma-ray sources around.

Aql X-1, the brightest X-ray source in the Aquilla constellation, is an X-ray millisecond pulsar in a binary system (see, e.g. Ref. [22] for discussion and references). The system is located at the distance of $5.2^{+0.7}_{-0.8}$ kpc from the Earth [23]. It experiences quasi-periodic outbursts each 300 days roughly (see the X-ray light curve in Fig. 3). Though the object is one of only twelve known

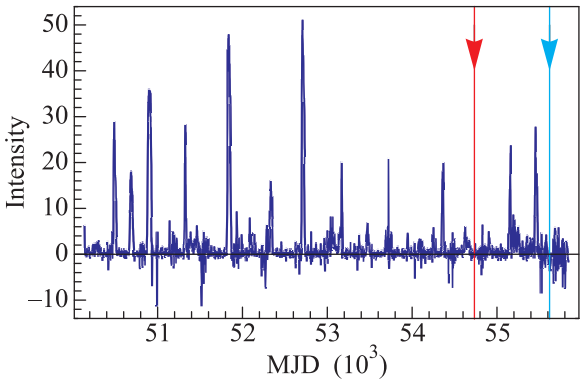

Fig. 3. The X-ray light curve of Aql X-1 (quick-look results provided by the ASM/RXTE team [24]). Vertical lines with arrows denote the arrival times of cosmic rays

Galactic accretion-powered millisecond pulsars [25] and is well studied, it does not appear very exotic. It is singled out of this dosen only by a relatively large mass of the companion in the binary system, $M \gtrsim 0.45 M_\odot$, and the correspondingly large orbital period of ~ 19 h. The estimated magnetic field on the neutron-star surface is $\sim (1 \ldots 5) \cdot 10^8$ G [26, 27]. On the basis of X-ray timing and spectral properties, this object is classified as "atoll" (see, e.g. Ref. [28] for a more detailed discussion of classifications). Accretion in these sources may have similarities with accretion on stellar-mass black holes [29].

An extragalactic $E \sim 10^{20}$ eV proton arriving from the direction we consider should be deflected by the magnetic field of the Milky Way by $\sim (2-4)^\circ$, depending on the field model which is not known precisely. However, a hypothetical particle coming from Aql X-1 would be deflected by a much smaller amount because the source is considerably closer to the Earth than the Galcatic Center is. Assuming charge one and the mean Galactic magnetic field in the disk of ~ 1 μG, one obtains a rough estimate for the deflection of $\sim 1.1^\circ$. This deflection would correspond, for a proton, to the time delay of $\sim$ yr, thus making it not surprising that the arrival times of the events do not coincide with particularly interesting moments in the life of the would-be source, cf. Fig. 3 (unless neutral primaries are assumed). We note that currently, neither PAO nor TA is able to determine the primary particle type of a particular air shower detected by the surface array.

In general, a wide belief that cosmic rays with $E \gtrsim \gtrsim 10^{19}$ eV are of extragalactic origin is based on a few reasonable arguments. First, these energetic particles are not confined by the Galactic magnetic field and, assuming similar fields exist in other galaxies, are not confined anywhere. Second, the arrival directions of these cosmic rays are (almost) isotropic on large angular scales, while the distribution of any kind of Galactic sources on the sky is anisotropic. Third, there is a lack of Galactic objects where sufficient conditions for acceleration of particles to those energies are satisfied. Nevertheless, some proposals for Galactic sources are being discussed (see, e.g. Refs. [30–32]).

The first two arguments might be overcome if in the Milky Way there are only a few sources of cosmic rays. Then, part of the observed events come from these few Galactic sources and the rest comes from similar sources in nearby galaxies (thus explaining weak hints of correlation with the local distribution of matter at the highest energies). However, Galactic sources should then dominate the flux at high energies (cf. e.g. Ref. [33]) thus producing either the Galactic anisotropy or a concentration of arrival directions towards particular sources. A price to pay for not seeing this in data is the fine tuning which is however not excluded.

As for the third argument, acceleration of UHECRs in pulsars has been proposed long ago in Ref. [34] (see Ref. [32] for a different recent proposal). In general, it is difficult to overcome radiative energy losses in pulsar magnetosphere [2, 35]; however, in the regime where the losses are dominated by the curvature radiation and the electric and magneic fields are parallel in a very long tube ("linear accelerator"), the energy-loss limits may be relaxed [2, 35]. Another problem with pulsars is the screening of the accelerating potential gap when electron-positron pairs are created; however, one expects that some pulsars are "pair-starved" [36, 37] and may accelerate particles to higher energies. It is presently unclear whether these conditions are satisfied in Aql X-1.

To summarize, we observe an interesting coincidence of the arrival directions of two out of six cosmic-ray particles with estimated energies in excess of 10^{20} eV observed by the modern surface-detector arrays, the Pierre Auger Observatory and the Telescope Array experiment. The probability that one or more doublets occur in the data set by a fluctuation of the isotropic flux is about $3 \cdot 10^{-3}$. The error circle of the arrival directions of coinciding cosmic rays includes a bright accretion-powered millisecond pulsar in the X-ray binary Aql X-1. Future studies are required to support or reject the conjecture that Galactic sources are able to produce super-GZK cosmic rays and whether this particular source possesses physical conditions allowing for particle acceleration to that high energy.

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