Detection prospects of the Telescope Array hotspot by space observatories

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In the present-day cosmic ray data, the strongest indication of anisotropy of the ultrahigh energy cosmic rays is the 20-degree hotspot observed by the Telescope Array with the statistical significance of 3.4σ. In this work, we study the possibility of detecting such a spot by space-based all-sky observatories. We show that if the detected luminosity of the hotspot is attributed to a physical effect and not a statistical fluctuation, the KLYPVE and JEM-EUSO experiments would need to collect $\sim$300 events with $E > 57$ EeV in order to detect the hotspot at the 5σ confidence level with the 68% probability. We also study the dependence of the detection prospects on the hotspot luminosity.

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I. INTRODUCTION

Both cosmic ray protons and nuclei at the highest energies cannot reach us from cosmological distances due to energy losses on the cosmic microwave background and infrared backgrounds. The cutoff in the ultrahigh energy cosmic ray (UHECR) spectrum was predicted by K. Greisen, G. Zatsepin, and V. Kuzmin in 1966 [1] and was observed first by the HiRes experiment in 2002 [2] and later confirmed with larger statistical significance by the Pierre Auger Observatory [3] and Telescope Array [4].

The presence of the cutoff in the UHECR spectrum implies that cosmic rays at the highest energies come from the nearby Universe. At energies $E \gtrsim 60$ EeV one expects that most of the cosmic rays come from local sources with $z < 0.1$. One can hope to find those sources by correlating the arrival directions of the cosmic ray events with catalogs of astrophysical sources.

However, charged cosmic rays are deflected from the sky positions of their sources by both the galactic and intergalactic magnetic fields. For UHECR protons with $E \gtrsim 60$ EeV, the deflections in the galactic magnetic field are not large, $\delta_{\rm Gal} \sim 2°(Z/1)(B/\mu G)(60\,{\rm EeV}/E)$. According to modern models of the galactic magnetic field [5,6], this is true for outside of the galactic plane in most of the sky. Much less clear is the situation with the extragalactic magnetic fields. Faraday rotation measures of extragalactic sources set an upper bound on such fields at a nanoGauss level [7]. Different numerical simulations show contradicting results from very small deflections $\delta_{\text{extra-Gal}} < 1°$ outside of galaxy clusters [8] to as large as tens of degrees $\delta_{\text{extra-Gal}} > 10°$ [9].

Assuming that deflections in the extragalactic magnetic fields are small one can expect a small-scale (of the order of a few degrees) correlation between arrival directions of UHECR events and positions of sources located in the large-scale structure. However, the search for such correlations with point sources was not successful. First positive hints of correlations with point sources found in the Auger data [10] were not confirmed by the later data of both Auger [11] and Telescope Array (TA) experiments [12]. At larger angular scales, the results of the full-sky harmonic analysis [13] also suggest that deflections are larger than what follows from the above estimate [14]. These negative results indicate either the presence of a large fraction of intermediate/heavy nuclei at $E \gtrsim 60$ EeV or large extragalactic magnetic fields, or both.

The Auger experiment has detected a change of composition towards heavy nuclei at high energies [15]. In particular, the most recent measurements in combination with post-LHC hadronic models show the absence or a small fraction of both protons and iron at $E > 40$ EeV [16]. The TA data are consistent with protons for pre-LHC models, but do not have sensitivity to distinguish protons from intermediate nuclei at $E > 40$ EeV [17]. On the other hand, joint analysis of both experiments has shown a consistency of the experimental data on composition between TA and Auger [18] within estimated errors. A solution consistent with currently existing data could be that UHECRs at $E > 40$ EeV are largely composed of intermediate-mass nuclei, and their deflections prevent us from finding sources by correlating arrival directions with the source positions at small angles.

Another possibility to look for sources of UHECRs is to use the autocorrelation function of cosmic rays. This function is not very sensitive to deflections in the regular field, which can help to find sources even for nuclei primaries. The combined data of AGASA and HiRes experiments already indicate a possible anisotropy at $E > 40$ EeV and the 20-degree angular scale [19]. A similar anisotropy was found later in the Auger data, which show an excess in the circle of 18° radius centered near Cen A

[20]. The significance of anisotropy towards Cen A has not improved in later data.

Finally, the Telescope Array detected a hotspot in the Northern hemisphere using the five-year data recorded up to May 4, 2013 [21]. The hotspot was a cluster of 19 events with energies > 57 EeV occupying a 20°-degree radius circle centered at R.A $= 146.°7$, Dec $= 43.°2$, near the Ursa Major cluster of galaxies. The *pretrial* statistical significance of the hotspot equals 5.1σ, with the *post-trial* probability of it appearing by chance in an isotropic cosmic ray sky estimated as 3.4σ. With the additional two years of data taking, the statistics is not yet enough to confirm the result: the number of events in the hotspot increased up to 24 but the statistical significance of the excess remained the same [22].

The TA experiment alone can confirm this result in the next few years after the four-times extension, but an independent confirmation by a different experiment will be important. In particular, future space-based instruments like KLYPVE [23,24] or JEM-EUSO [25] can do this job. In this work, we study the discovery potential of these experiments for an independent detection of the TA hotspot.

II. KLYPVE AND JEM-EUSO EXPOSURE

In order to simulate the distribution of the *detected* cosmic ray events in the arrival directions, one needs to know the exposure of the experiment as a function of the direction in the sky. Both KLYPVE and JEM-EUSO are planned for deployment at the International Space Station. The two instruments are different in design but employ the same technique for detecting UHECRs. They will register the near-ultraviolet fluorescent light generated by secondary particles in extensive air showers born in the atmosphere by primary UHECRs, and the Cherenkov light reflected at the surface of the Earth. The expected exposure of JEM-EUSO (in nadir observation) was studied in detail in [26]. It was shown that the experiment will cover the whole celestial sphere with the integrated exposure only slightly depending on declination δ and being uniform with respect to right ascension. The dependence of exposure on declination obtained in [26] can be approximately expressed as

$$R(\delta) = 1 + 0.0185\sin^4\delta + 0.0192\sin^6\delta - 0.006. \quad (1)$$

This exposure is nearly uniform over the sphere, with variations not exceeding a few percent. Since both experiments will have the same orbit and share the same principle of detecting UHECRs, Eq. (1) can be used for the KLYPVE mission, too.

Exposure of both detectors depends on the energy of primary particles but they are expected to be fully efficient at energies above ≈50–60 EeV [24,27,28]. Thus, this dependence is not important for what follows since we present the results directly in terms of the total number of events with energies exceeding 57 EeV.

III. HYPOTHESES TO BE TESTED

In this paper, we consider two alternative hypotheses concerning the sky distribution of UHECRs with $E > 57$ EeV:

H0: isotropic distribution.

H1: isotropic distribution superimposed with the hotspot of a given relative intensity.

Under H0 we generate isotropic events and then modulate their distribution with the KLYPVE exposure (1).[1]

When generating the events that follow H1 for given hotspot parameters, we first generate the hotspot events that follow the Gaussian distribution of a given width and position. Isotropically distributed events are then added in such a way that the fraction f of the hotspot events in the combined set equals the given value. Finally, the resulting set is modulated with the exposure (1).

In this paper, we use the hotspot parameters from Ref. [21]. The right ascension and declination of the center are taken to be 146.°7 and 43.°2 respectively. The uncertainty in the position of the center is 2.7°. In Ref. [21], the hotspot was fitted with the Gaussian shape plus a uniform background. The width of the spot was found to be 10.3° with the uncertainty of 1.9°. The amplitudes of the Gaussian part and the uniform background can be converted into the fraction f of the hotspot events as would be seen in the case of a uniform exposure. This gives $f = 0.084$ with the uncertainty $\sigma_f = 0.036$.

IV. PROSPECTS OF DETECTING THE TA HOTSPOT BY SPACE OBSERVATORIES

To quantify the discovery potential of the KLYPVE and JEM-EUSO missions with respect to the TA hotspot, we calculate how many events should be observed in order to establish its existence at 5σ confidence level (C.L.). More specifically, for a given number of observed events N we generate many simulated data samples following H1. Each sample has the hotspot parameters picked randomly from a Gaussian distribution centered at the values measured by the TA [21] with the width equal to the corresponding standard deviation. The parameters over which the marginalization is performed include the hotspot position and width. We do not marginalize over the hotspot intensity; instead, three values are considered: the central value that corresponds to $f_0 = 0.084$, and the optimistic/pessimistic cases $f_\pm = 0.084 \pm 0.036$.

For each generated sample we calculated the value of the test statistics (TS). Several test statistics were considered: the number of events n_s in the circle of radius 20° fixed at the position of the TA hotspot, as well as the first five

[1]An isotropic flux obeying exposure (1) can also be simulated using the standard inverse transformation method. Our calculations show that both approaches provide identical results but the first one is more efficient on computer time.

spherical harmonic coefficients C_l with $l = 1, \ldots, 5$. We have found that the first test statistics is much more sensitive than the others, the reason being that it incorporates information about the exact hotspot location, while the harmonic coefficients C_l are rotationally invariant. In what follows we present the results for this TS only.

By generating a large number of samples at fixed N and fixed hotspot intensity, we constructed a distribution of TS, n_s. From this distribution we determined the value $\overline{n}_s$ of the TS such that 68% of realizations have equal or larger value of n_s.

We then generated many samples of N events corresponding to no-signal hypothesis H0, calculated the TS for each of them, and obtained the distribution of the TS under H0. Since we are interested in the 5σ C.L., the number of isotropic samples has to be at least 10^7. Note, however, that the distribution of the TS for the isotropic hypothesis is known analytically: this is just a binomial distribution fully characterized by the "number of trials" N and the "probability of success in a single trial" p_0. The latter is just the probability that a single observed event will be found in the hotspot region. This probability is much easier to calculate numerically; we have found $p_0 = 0.0302$, including the effect of nonuniform exposure. Other properties of this distribution, in particular, the probability to have n or more events in the spot out of N total, can be calculated analytically.

Having obtained $\overline{n}_s$ for given values of N and the spot intensity f, as well as the distribution of the TS under H0, we finally determine the probability to have, in an isotropic set, the TS n_s larger than or equal to $\overline{n}_s$ (that is, $\overline{n}_s$ or more events inside the spot region). This probability, interpreted as Gaussian and converted into standard deviations, gives the C.L. at which the isotropy hypothesis H0 can be ruled out in 68% of cases for given N and f. The whole procedure is illustrated in Fig. 1 for particular values of parameters as explained in the caption.

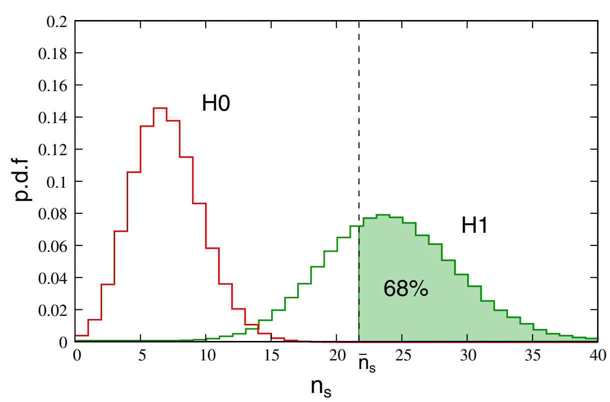

FIG. 1. Probability distributions of the number of events n_s in the TA hotspot region for the isotropic distribution (H0) and in the case of the hotspot with parameters as determined by TA [21] (H1). The total number of events is 250. The vertical line shows the value $\bar{n}_s$ such that 68% of realizations have the signal at least that strong.

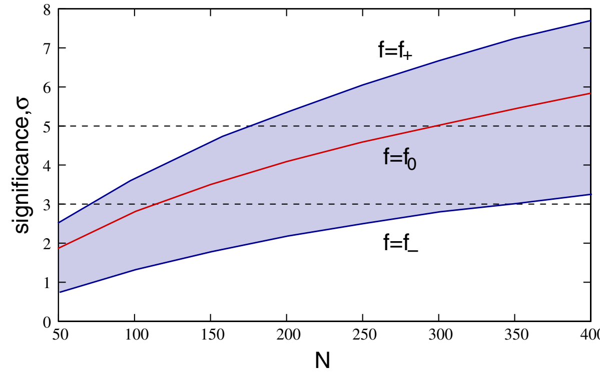

FIG. 2. The significance of the isotropy hypothesis rejection as a function of the total number of detected events N. The central curve (red) $f = f_0$: hotspot brightness as deduced from the five-year TA data. The shaded band: corresponding 1σ uncertainty. Horizontal dashed lines show the 3σ evidence and 5σ discovery levels.

Figure 2 shows the dependence of the significance at which the isotropy hypothesis H0 can be ruled out as a function of the observed number of events N for three values of the spot intensity $f = f_0$, $f_\pm$ in the best 68% of cases.

The significance is shown in terms of Gaussian standard deviations σ. Horizontal lines at 3σ and 5σ represent the standard evidence and discovery levels. The red curve in the middle corresponds to the brightness of the spot as deduced from the five-year TA data. Upper and lower blue lines represent the 1σ uncertainty of the hotspot brightness.

If the central value for the hotspot brightness is assumed, then 3σ detection can be expected with ~120 events, while a 5σ discovery will require the observation of ~300 events with $E > 57$ EeV. In case of the optimistic scenario these numbers change to 70 and 170, respectively. In case of the pessimistic scenario the evidence will be obtained with ~350 events, while the discovery will require accumulation of ~1000 events with $E > 57$ EeV.

Will KLYPVE or JEM-EUSO be able to register the necessary number of events? It was estimated recently that with the annual exposure $\sim 5 \times 10^4$ km^2 sr above ~60 EeV, JEM-EUSO will collect 429 events/yr, or about 2,145 events in five years [28]. In a similar fashion, one can estimate that with the annual exposure $\sim 1.2 \times 10^4$ km^2 sr, KLYPVE will detect more than 100 events every year of operation, and more than 600 events during its planned lifetime. Thus, both experiments have a strong discovery potential to detect the TA hotspot.

V. CONCLUSIONS

In this work, we studied the possibility of the TA hotspot detection by future space experiments like KLYPVE and

JEM-EUSO. We have seen that the perspectives of the hotspot detection depend strongly on the actual signal strength. If the mean strength derived from the five-year TA data is assumed, with ∼300 observed events with $E >$ 57 EeV the space observatories will have a 68% chance of the 5σ discovery. The number of events required for that would be ∼1000 in the case of the pessimistic scenario.

With its huge annual exposure (almost an order of magnitude larger than that of the Pierre Auger Observatory) and the planned five-year operation time, JEM-EUSO has excellent opportunities for confirming the existence of the TA hotspot at high confidence level. In six years of operation, KLYPVE will have the total exposure approximately $1/3$ of JEM-EUSO, and thus it also has a strong discovery potential, especially in the case in which the five-year flux registered by the Telescope Array persists.

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Note added—Recently, we became aware of a similar work reported at the 18th JEM-EUSO International Meeting (Stockholm, December 7–11, 2015) [29]. As far as we understand, the results presented there were obtained in a different fashion but are close to our own.

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