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On active galactic nuclei as sources of ultra-high energy cosmic rays

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ABSTRACT

We measure the correlation between sky coordinates of the *Swift* Burst Alert Telescope (BAT) catalogue of active galactic nuclei (AGN) with the arrival directions of the highest energy cosmic rays detected by the Auger Observatory. The statistically complete, hard X-ray catalogue helps to distinguish between AGN and other source candidates that follow the distribution of local large-scale structure. The positions of the full catalogue are marginally uncorrelated with the cosmic ray arrival directions, but when weighted by their hard X-ray flux, AGN within 100 Mpc are correlated at a significance level of 98 per cent. This correlation sharply decreases for sources beyond ∼100 Mpc, suggestive of a GZK suppression. We discuss the implications for determining the mechanism that accelerates particles to these extreme energies in excess of 10^{19} eV.

Key words: cosmic rays – galaxies: active – galaxies: nuclei.

1 INTRODUCTION

The recent announcement of anisotropy in the arrival directions of ultra-high energy cosmic rays (UHECRs) by the Auger Collaboration (Abraham et al. 2007, 2008) has yielded much interest. By correlating the UHECR arrival directions with the positons of nearby active galactic nuclei (AGN) on the sky, they suggest that AGN are responsible for accelerating these particles.

Modern experiments are approaching the size and sophistication needed to measure the energy and direction of UHECRs with enough precision to reliably determine their sources. The Auger Observatory combines measurements of Čerenkov radiation from particle interactions in surface detectors and fluorescence from molecules in the atmosphere excited by the cascade (Abraham et al. 2004). For reviews of earlier experimental work, see Nagano & Watson (2000), Cronin (2005) and Sokolsky & Thomson (2007).

The origin of particles with energies $\gtrsim 10^{19}$ eV has been a long-standing mystery in high energy astrophysics (see Hillas 1984, for a review). Supernovae, gamma-ray bursts, pulsars, shock fronts in galaxy clusters, decays of exotic massive particles, and various classes of AGN have all been proposed as acceleration or generation sites. All but the highest energy cosmic rays are thought to be significantly deflected by Galactic magnetic fields, which makes it difficult to trace arrival directions back to astronomical sources. Numerous attempts have been made to correlate different source catalogues with events observed by cosmic ray detectors including Yakutsk, Fly's Eye, AGASA, HiRes and now Auger (e.g. Stanev et al. 1995; Singh, Ma & Arons 2004; Gorbunov et al. 2007; Hague et al. 2007; Ivanov et al. 2008; Kashti & Waxman 2008). Related studies have analysed the auto-correlation of sources and events as well as the occurrence of multiple co-located UHECR detections to place constraints on the number of sources responsible for these events (Takeda et al. 1999; Cuoco et al. 2008). AGN have long been known to be capable of generating electric potential differences in excess of 10^{19} volts (Burns & Lovelace 1982), and given the further suggestion from the Auger team that their positions are correlated with UHECR arrival directions, we focus only on these objects.

The correlation of Auger events with extragalactic sources given by Abraham et al. (2008) is based on an inhomogeneous list of AGN collected from the literature (Véron-Cetty & Véron 2006, hereafter V-C). As pointed out by others (Kashti & Waxman 2008) and explained in the companion paper to the catalogue itself, the compilation is not complete and should not be used for statistical purposes. While using such a list can be adequate for disproving the hypothesis of an isotropic distribution of arrival directions, positive proof of correlation with sources calls for a statistically complete sample. Additionally, the distribution of local AGN is similar to that for all local large-scale structure. A complete sample of sources selected for a certain property can distinguish between different tracers of large-scale structure and also determine if a particular factor is relevant to UHECR acceleration.

In this letter, we study the correlation of Auger UHECR arrival directions with the positions of AGN from the hard X-ray selected *Swift* BAT catalogue (Tueller et al. 2008). Selection from the hard X-ray band reduces the bias due to absorption that impacts lower energy bands. Optically selected lists, including many that are compiled into the V-C catalogue, are less likely to include the obscured

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nuclei that make up an increasing fraction of the AGN population at low redshifts (Brandt & Hasinger 2005). Matt et al. (2000) deduce from hard X-ray observations that heavily obscured sources must locally outnumber unobscured sources by a large factor; the nearest three AGN are all highly obscured.

Since hard X-ray observations are less sensitive to obscuration, they provide a more accurate indicator of the accretion rate and the intrinsic luminosity of an AGN. We aim to test the idea that the intrinsic luminosity of an AGN is a sign of its particle accelerating ability by measuring the relation between hard X-ray flux and the positional correlation of AGN with UHECR arrival directions. In the next section, we will present the catalogues of UHECRs and AGN. Section 3 will describe the statistical tests used to measure correlation between the two lists as well as the results of these tests. We discuss the implications of these results and compare them to previous analyses in Section 4, and Section 5 concludes the letter.

2 DATA

In this section, we discuss the catalogues of UHECRs and AGN used for testing the correlation between events and sources. We do not combine data from different cosmic ray observatories because of possible inconsistencies in energy calibration and angular resolution. A statistically complete, hard X-ray selected sample of AGN will reduce the bias towards unabsorbed sources present in the V-C catalogue, which has mainly been selected from optical observations. This sample should clarify whether the accretion processes in AGN that generate hard X-rays are relevant to high energy particle acceleration. By narrowing the sample from a large and inhomogeneous list of AGN, we can test the possibility that the observed correlation of UHECRs and AGN is merely due to the fact that AGN are distributed similarly to other sources in the local structure.

2.1 UHECR events

The Auger Observatory (Abraham et al. 2004, 2008) has been operating stably in Argentina since 2004, using a hybrid system of telescopes to measure fluorescence in the atmosphere and water tanks to detect Čerenkov light from relativistic particles. The available UHECR list is comprised of 27 events with energies above 5.7×10^{19} eV from an integrated exposure of 9000 km^2 sr yr.

The relative exposure is independent of energy in this range, nearly uniform in right ascension, and has a declination dependence given by Sommers (2001). The latitude of the Auger Observatory is $-35\overset{\circ}{.}2$ and it has a maximum zenith angle acceptance of 60°.

The event arrival directions are determined with an angular resolution of better than 1°. However, magnetic fields of unknown strength will deflect charged particles on their trajectories through space. The advantage of studying the highest energy events is that this deflection is minimized, but it can still be up to $\sim 10^\circ$ in the Galactic field (e.g. Stanev 1997). Magnetohydrodynamical simulations of extragalactic fields have produced conflicting predictions for UHECR deflections, ranging from tens of degrees (Sigl, Miniati & Enßlin 2004) to less than a few degrees (Dolag et al. 2005).

2.2 AGN catalogue

We compare the arrival directions of Auger UHECRs with the locations of AGN in the *Swift* BAT survey. Details of the survey and results from the first three and nine months of observations are presented by Markwardt et al. (2005) and Tueller et al. (2008); we use a catalogue updated with the first 22 months of data.

The list includes 254 objects that have known redshifts and signal to noise ratios (S/N) greater than 4.8, corresponding to one false detection across the sky. Source identification is incomplete at low Galactic latitudes ($|b| < 15^\circ$), but the hard X-ray coverage (14–195 keV) provides a uniquely unbiased sample of local AGN over the rest of the sky. The median astrometric uncertainty is 1.7 arcmin and the limiting sensitivity is a few times 10^{-11} erg cm^{-2} s^{-1}. All but four sources in the 22-month catalogue have X-ray positions and spectra from previous observations or follow-up with the *Swift* X-Ray Telescope.

We restrict our statistical analysis to the complete sample within the Auger field of view ($S/N > 4.8$, $|b| > 15^\circ$, $\delta < 24\overset{\circ}{.}8$), leaving 138 AGN in the catalogue. For comparison with the original correlation between Auger events and AGN, there are 57 *Swift* sources within the Auger field of view at distances less than 100 Mpc, and six of these are not in the V-C catalogue. The V-C catalogue has 410 objects within 100 Mpc and the Auger field of view outside of the Galactic plane. Throughout this letter, distances are determined using a cosmology of $H_0 = 71$ km s^{-1} Mpc^{-1} and $\Omega_m = 0.27$ with a flat universe.

3 ANALYSIS

Fig. 1 shows the locations of Auger UHECRs and AGN from the BAT catalogue in supergalactic coordinates. The relative exposure of Auger observations is plotted in grey contours, and the AGN are shaded blue according to the product of their X-ray flux and the relative Auger observation time. Blue curves indicate where the BAT catalogue is incomplete at low Galactic latitudes, $|b| < 15^\circ$.

Visually, we can see several interesting correlations and non-correlations. Cen A is the brightest source and has two Auger events within 3°. The likelihood of observing 2 of the 27 events within this angular separation of the brightest AGN in the entire catalogue for an isotropic distribution of arrival directions in Auger's field of view is about 3×10^{-4}. The six AGN within 20 Mpc are marked with white crosses, and four of these (including Cen A) have UHECR arrival directions within 6°. If this proportion of observed UHECRs does in fact arrive from nearby AGN and the sources are roughly isotropic on large scales, we can infer that there must be significant propagation losses for cosmic rays from distant sources. However, clusters of two and three Auger events have no corresponding AGN, and the overall correlation is unclear. Certainly there is not a one-to-one correspondence between all of the observed UHECRs and a hard X-ray emitting AGN.

To quantify the likelihood that the two sets of locations arise from the same population of sources, we employ the two-dimensional generalization of the K–S test (Fasano & Franceschini 1987; Press et al. 2007). This test can be used to compare a data sample against a model distribution or to compare the properties of two data samples against each other. To test the null hypothesis that a given class of sources is responsible for UHECRs, one could construct a model of the expected cosmic ray flux map using a catalogue of positions, intrinsic luminosities, distances, expected absorption losses and the detector acceptance as a function of position. Additionally, one should account for interactions with background radiation which produce propagation losses known as the GZK effect (Greisen 1966; Zatsepin & Kuz'min 1966). Singh et al. (2004) used this approach to measure the correlation of infrared galaxies with UHECR events observed by AGASA, including models for the injection spectra and propagation effects.

We might expect the hard X-ray flux, as a measure of the intrinsic power of the source, to be a reasonable proxy for the

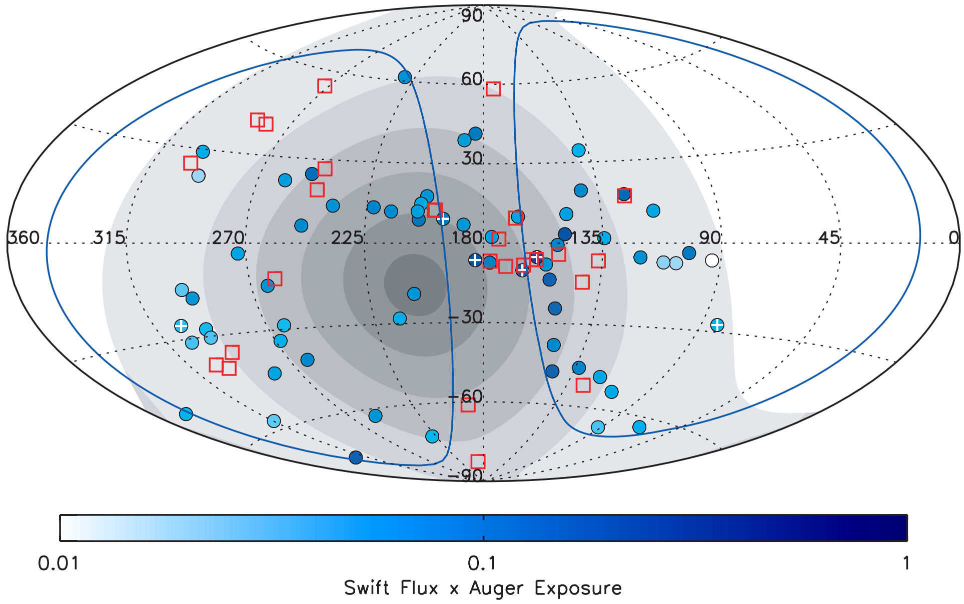

Figure 1. Map of Auger UHECRs (open red squares) and BAT AGN within 100 Mpc (filled blue circles) in supergalactic coordinates (de Vaucouleurs, de Vaucouleurs & Corwin 1976). The blue colour depth is scaled by the hard X-ray flux and Auger exposure, relative to Cen A. The six AGN in the catalogue within 20 Mpc are marked with white crosses, with Cen A at (159°.7, −5°.2). Grey contours have equal integrated exposures. Blue boundaries show where the AGN catalgoue is incompete due to the Galactic plane, $|b| < 15°$.

cosmic ray flux. But because a model of GZK effects requires an input spectrum of cosmic rays and the injection mechanism is unknown, we opt to begin by simply comparing the AGN locations with the UHECR arrival directions. Subsequently, we weight these positions by the product of the X-ray flux and the relative Auger exposure.

The two-dimensional K–S test measures the fraction of data points lying in the natural quadrants defined around each data point. The statistic D is the maximum difference between the fractions of each of the two data sets that lie in a quadrant, found after iterating over all points and their respective quadrants. The strength of the correlation between two catalogues is reported as the integral probability distribution $P(D\sqrt{n} >$ observed), where $n = N_1N_2/(N_1 + N_2)$, and N_1 and N_2 are the number of data points in the two sets. This measurement can be used to determine the similarity of sets of positions on the sky. Statistically speaking, high values of P do not *prove* the null hypothesis that the two catalogues arise from the same population, but low values ($P \lesssim 20$ per cent) call for the rejection of that null hypothesis.

The probability that the two sets of data are from the same population can be determined with an analytical approximation if the number of data points is sufficient, but due to the limited number of events available and the irregular shape of the allowed coordinate plane, we generate Monte Carlo simulations of cosmic ray arrival directions to compare with the observed events. For each set of AGN considered, 10 000 lists of positions are randomly generated in a distribution on the sky that is proportional to the Auger exposure, excluding low galactic latitudes. Each list has the same number of UHECRs as observed in the selected region, and has its D statistic calculated in the same way as the real data. The significance of the correlation between a catalogue of AGN and the observed UHECRs is reported as $P(D\sqrt{n} >$ observed), which is the percentage of randomly generated UHECR lists that have a higher value of $D\sqrt{n}$ than the real data under consideration. Thus, extreme values of P suggest that the observed events are not distributed isotropically, and high (low) values indicate a good (poor) correlation between the Auger UHECRs and the given AGN list.

It is important to ensure that the test does reliably differentiate between a set of points correlated with a reference catalogue and an isotropically distributed set. We picked random subsets of AGN from the larger V-C catalogue to serve both as a list of AGN and a list of UHECRs, with the number of sources and events equal to those in the actual tests on *Swift* and Auger data. Average values for the correlation showed $P \gtrsim 70$ per cent, setting a rough threshold for accepting that two data sets belong to the same distribution.

The test differs from the one performed by the Auger team in that the angular distance between the source position and arrival direction is not a parameter of the fit, so it is not as sensitive to the undetermined size of magnetic deflections. The angular scale of the test's sensitivity is not clearly defined and depends on the separation of points in the data set, but Monte Carlo simulations indicate that correlations decrease monotonically with angular separation, and that this decline has a scalelength of approximately 10–15°. Additionally, we use the full energy range of the published Auger UHECR catalogue, which has a threshold selected to maximize the correlation in their analysis. We allow source distances in the full range of the AGN catalogue, though completeness becomes an issue at higher distances.

In our application, we use the equatorial positions for the Auger events and *Swift* AGN as the data points. Restricting the data sets to regions and significance levels where the BAT catalogue is complete ($|b| > 15°$, S/N ≥ 4.8) and to where the Auger exposure is non-zero ($\delta < 24°.8$) leaves 138 AGN and 19 UHECRs. For these catalogues, we measure $P = 50$ per cent. This value jumps to 98 per cent after weighting the AGN coordinates by their hard X-ray flux and relative Auger exposure. If we cut the AGN catalogue to those 57 with distances less than 100 Mpc, the unweighted probability is 84 per cent. The flux-weighted value is unchanged, indicating that the correlation is dominated by nearby, bright sources. However, the removal of Cen A does not alter the correlation values by more

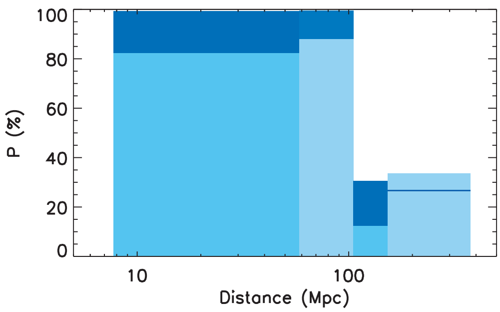

Figure 2. Redshift dependence of the correlation between AGN positons and UHECR arrival directions. Light (dark) boxes show the unweighted (flux-weighted) values of *P*, defined in the text. In the most distant bin, flux-weighting decreases the significance of the correlation. There are 30 AGN in each comoving distance bin.

than a few per cent. Cuts on the catalogue to distances smaller than 100 Mpc do increase the correlation slightly, but quickly the number of sources becomes too small to obtain reliable values from the test. For comparison, the 410 sources in the V-C catalogue with $d < 100$ Mpc, $|b| > 15°$, and $\delta < 24.°8$ produce a correlation with the UHECRs of only 55 per cent.

To determine the redshift dependence of the correlation, we test four redshift-sorted bins of 30 AGN each, with mean commoving distances of 35, 80, 131, and 248 Mpc. The results are plotted in Fig. 2, which shows a clear decrease in the correlation at larger distances. Replicating the plot with different bin sizes, we consistently see a sharp decrease in the correlation near 100 Mpc.

We performed a similar test on the luminosity dependence of the *P* values and found that the correlation in the full catalogue is actually lower for more luminous sources than for dimmer ones. It is possible that the strong radiation field surrounding luminous AGN interferes with UHECR propagation (Dermer 2007). But when restricting the AGN to distances less than 100 Mpc, the trend reverses and more luminous sources tend to correlate better than less luminous ones. In both cases, the most powerful AGN are at a higher average distance than dim ones. We interpret these results to imply that the cosmic ray flux is correlated with the luminosity of AGN, but propagation losses on a distance scale of ~100 Mpc interfere with the effect.

We would also like to test the correlation for subclasses of AGN. There are 46 ‘Type 1’ objects (Seyfert 1/1.2 galaxies) and 53 ‘Type 2’ objects (Seyfert 1.8/1.9/2 galaxies) at high Galactic latitudes and within the Auger exposure. There are not enough objects in other subclasses such as blazars or quasars to obtain statistically significant results. For Type 1 objects, the unweighted and weighted *P* values are 59 and 96 per cent, respectively, while for Type 2 objects these values are 53 and 99 per cent. For both types, excluding sources at distances greater than 100 Mpc increases the unweighted correlation by ~30 percentage points, while the flux-weighted values remain the same.

The overall results are consistent with visual expectations, in the sense that the correlation between the full catalogues is marginal at best, but various cuts and weighting factors can improve the correspondence. We risk falling into the trap of using *a posteriori* cuts to find the best matches and reporting prejudical results. Lengthy arguments have taken place over the usefulness of applying ‘penalty factors’ to account for the statistical biases produced by these cuts (Evans, Ferrer & Sarkar 2003; Finley & Westerhoff 2004), but we omit this type of analysis and merely point out that the stated probabilities should be taken with these caveats in mind.

4 DISCUSSION

Our results from the K–S tests do not cause us to reject the null hypothesis that AGN are the source of UHECRs, in disagreement with the conclusion of Gorbunov et al. (2007). On the contrary, we find significant correlations that suggest that AGN are the sources of UHECRs, supporting the claims of Abraham et al. (2007). The hard X-ray catalogue used in this letter produces a higher correlation with UHECR arrival directions than the larger V-C catalogue which was previously tested. From this information alone, it is still possible that another type of source with a local distribution similar to that of AGN is responsible for UHECR acceleration. But when weighting by the hard X-ray flux or selecting the most luminous nearby sources, the measured correlation between AGN and UHECRs increases. Thus, a confounding class of sources would have to trace both the local spatial and luminosity distributions of AGN, which seems unlikely.

If AGN are positively identified as the sources of UHECRs, the second main result of this letter is the significant decline in correlation at a distance of ~100 Mpc. This drop is predicted from the GZK cut-off, which suggests that the flux of cosmic rays in the energy range considered here is depleted due to photopion production and pair creation from interactions with the cosmic microwave background. For cosmic rays with energies above 5×10^{19} eV, the observable ‘horizon’ is expected to be of order 100 Mpc, with deviations due to the distribution of sources and the masses of accelerated nuclei (Harari, Mollerach & Roulet 2006). HiRes has detected a suppression of the cosmic ray spectrum at energies above 6×10^{19} eV which has been attributed to the GZK cut-off (Abbasi et al. 2008). Though this detection has been supported by the Auger data, it is conceivable that the intrinsic spectrum of cosmic rays falls off at this energy due to some cut-off in the acceleration mechanism. An observation that UHECRs arrive from nearby sources and not distant ones would provide direct evidence for the GZK effect.

The drop observed in the correlation between AGN positions and UHECR arrival directions at 100 Mpc, as shown in Fig. 2, is suggestive of such a suppression. It may arise due to other effects including increased angular deflections due to extragalactic magnetic fields and incompleteness of the AGN catalogue beyond this distance (Abraham et al. 2008). However, if magnetic deflections are the culprit we would expect the correlation to begin decreasing before 100 Mpc, which is not observed. Catalogue incompleteness affects the detection of less luminous AGN at large distances, but for local AGN the correlation reduces with faintness. Additionally, the evidence discussed earlier that four nearby AGN have associated events does, from Olber’s paradox considerations, strongly argue that the sources of all detected UHECRs are at very low redshift.

The association of two UHECRs with the brightest AGN in the *Swift* catalogue allows for speculation about the nature of particle acceleration mechanisms. Several studies have suggested that blazars are likely candidates for UHECR sources (e.g. Tinyakov & Tkachev 2001), though the Auger data do not support a correlation (Harari et al. 2007). Cen A is a nearby jetted AGN with two large radio lobes visible from the side. If Cen A is in fact responsible for some of the observed UHECRs, then cosmic rays do not need to be emitted directly along a jet towards the observer. It is conceivable that jets may still be important for cosmic ray acceleration and that the events seen towards Cen A were deflected by strong magnetic fields surrounding the AGN. Our division of the AGN catalogue into ‘Type 1’ and ‘Type 2’ classes yielded similar results from the K–S test for correlation, but further tests on distinct classes of AGN, including more heavily obscured sources,[1] will help clarify which mechanism or orientation is necessary to produce the observed UHECRs.

As data for a larger number of UHECRs become available, we will be able to further differentiate between the properties of acceleration sites. We have shown that the correlation between AGN positions and UHECR arrival directions does vary with the hard X-ray flux and the distance to the source. It will be interesting to test other properties to constrain models for the acceleration mechanism. Black hole spin may be an important parameter but has not yet been tested because of the difficulty in measuring its value for a sizable sample of sources. Many models exist for the extraction of energy from black holes (e.g. Blandford & Znajek 1977), and a further analysis of the influence of the model parameters on the correlation between source positions and UHECR directions will more precisely determine which sources are accelerating these particles. Conversely, when the cosmic ray sources are clearly identified, more detailed observations in the realm of particle astronomy will improve our understanding of the physical mechanisms taking place in these sources.

5 CONCLUSION

We have measured the correlation between the positions of the *Swift* hard X-ray selected catalogue of AGN and the arrival directions of UHECRs observed by Auger. No significant correlation is found for the full catalogue, but imposing weights based on the expected cosmic ray flux results in a correlation with a significance level of 98 per cent. A steep drop in the correlation for sources beyond 100 Mpc suggests that the GZK effect does suppress the cosmic ray flux at these energy and distance scales.

Though our study lends support to the claims of the Auger Collaboration that AGN are responsible for UHECRs, the connection should still be tested with better statistics as observations continue. The identification of two UHECRs from the direction of Cen A and the improvement of the correlation when weighting by hard X-ray flux offer tantalizing hints about the acceleration mechanism. Though the nature of these exotic UHECRs remains largely unknown, future studies in particle astronomy may lend insight into other areas such as Galactic and extragalactic magnetic fields and the physics behind AGN engines.

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[1] We searched for a correlation with several heavily obscured sources too faint to be detected in the BAT catalogue, selected from Levenson et al. (2006). We have not identified any obscured AGN located near the UHECR arrival directions, but the sample size is too small to draw conclusions about this population of AGN in relation to the UHECRs.

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