Ultra-high energy cosmic rays, spiral galaxies and magnetars

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Accepted 2008 August 11. Received 2008 July 29; in original form 2008 June 14

ABSTRACT
We measure the correlation between the arrival directions of the highest energy cosmic rays detected by the Pierre Auger Observatory with the position of the galaxies in the H I Parkes All-Sky Survey (HIPASS) catalogue, weighted for their H I flux and Auger exposure. The use of this absorption-free catalogue, complete also along the Galactic plane, allows us to use all the Auger events. The correlation is significant, being 86.2 per cent for the entire sample of HI galaxies, and becoming 99 per cent when considering the richest galaxies in HI content or 98 per cent with those lying between 40 and 55 Mpc. We interpret this result as the evidence that spiral galaxies are the hosts of the producers of ultra-high energy cosmic rays and we briefly discuss the classical (i.e. energetic and distant) long gamma-ray burst (GRBs), short GRBs, as well as newly born or late-flaring magnetars as possible sources of the Auger events. With the caveat that these events are still very few, and the theoretical uncertainties are conspicuous, we found that newly born magnetars are the best candidates. If so, they could also be associated with sub-energetic, spectrally soft, nearby, long GRBs. We finally discuss why there is a clustering of Auger events in the direction on the radio galaxy Cen A and an absence of events in the direction of the radio galaxy M87.

Key words: cosmic rays – galaxies: statistics – gamma-rays: bursts – radio lines: galaxies.

1 INTRODUCTION
The origin of ultra-high energy cosmic rays (UHECRs), exceeding 10 EeV (1 EeV = 1018 eV), has been a mystery for decades, but the recent findings of the large area detectors, such as the Akeno Giant Air Shower Array (AGASA; Ohoka et al. 1997), the High Resolution Fly’s Eye (HiRes: Abe-Zayyad et al. 2000) and especially the Pierre Auger Southern Observatory (Abraham et al. 2004), began to disclose crucial clues about the association of the highest energy events with cosmic sources. The Auger collaboration (Abraham et al. 2007) found a positive correlation between the arrival directions of UHECR with energies greater than 57 EeV and nearby active galactic nuclei (AGN) (in the optical catalogue of Véron-Cetty & Véron 2006). Although this result has not been confirmed by HiRes (Abbas et al. 2008) and criticized by Tavani et al. (2008), it received an important confirmation by George et al. (2008), who considered a complete sample of nearby hard X-ray emitting AGN detected by the BAT instrument onboard Swift. This sample is much less affected by absorption than any optical sample although, to identify as such an AGN, one relies on optical identification. Moreover, George et al. (2008) found a correlation not simply with the AGN locations, but by weighting them for the X-ray flux and the Auger exposure.

This association, if real, is surprising, since the large majority of the correlating AGN are radio quiet, a class of objects not showing, in their electromagnetic spectrum, any sign of non-thermal high-energy emission: no radio-quiet AGN was detected by the EGRET instrument onboard the Compton Gamma-Ray Observatory (Hartman et al. 1999). Therefore, they must accelerate particles (protons, nuclei, and presumably the accompanying electrons) to ultra-high energies without any notable radiative emission from these very same particles. Radio-loud AGN, instead, together with gamma-ray bursts (GRBs) (of both the long and short categories) do show high-energy non-thermal emission, and have been considered for a long time better candidates as UHECR sources (Milgrom & Usov 1995; Vietri 1995; Waxman 1995; Torres & Anchordoqui 2004; Dermer 2007; Murase et al. 2008; Wang, Razzaque & Meszaros 2008 for reviews, and Moskalenko et al. 2008; Nagar & Matulich 2008 for the possible association of the AUGER events with radio-loud AGN). Note also that some short GRBs could be due to the giant flares of highly magnetized neutron stars (‘magnetars’, as the 2004 December 27 event from 1806–1820; Borkowski et al. 2004; Hurley et al. 2005; Terasawa et al. 2005), and, at birth, a fastly spinning magnetar can be much more energetic than when, later, it produces giant flares (Arons 2003).

The possibility that GRBs and magnetars are the sites of production of UHECR would directly imply the direct association of these events with (normal) galaxies. In this case, the found association of UHECR with nearby AGN might then be due to the fact that...
local AGN just trace the distribution of galaxies. The aim of this Letter is to test this possibility directly correlating the locations of the ultra-high energy Auger events with a well defined, complete and possibly absorption-free sample of galaxies. For this purpose, we use the sample of H I emitting galaxies, compiled using the Parkes 64-m radio telescope (Staveley-Smith et al. 1996; Barnes et al. 2001), which is conveniently located in the south hemisphere, as the Auger observatory. The entire sample covers the portion of the sky visible by Auger, making it possible to use, for the correlation analysis, all the 27 UHECR events with energies larger than 57 EeV detected by Auger, without excluding the Galactic plane, as are instead necessary when dealing with AGN or optically selected galaxies. Note that the presence of neutral hydrogen strongly favours spirals (or, more generally, gas-rich galaxies) with respect to elliptical galaxies.

We use a cosmology with $H_0 = \Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$.

## 2 DATA

### 2.1 UHECR events

The Auger observatory (Abraham et al. 2004, 2008), operating in Argentina since 2004, is located at latitude $-35.2$ and it has a maximum zenith angle acceptance of 60°. The relative exposure is independent of the energy of the detected events and it is a nearly uniform in right ascension. The dependence on declination is given by Sommers (2001). The observatory can detect cosmic rays from sources with declination $\delta < 24^\circ/8$.

The available Auger list of UHECR events (Abraham et al. 2008) comprises 27 events with energies in excess of $5.7 \times 10^{19}$ eV from an integrated exposure of 9000 km$^2$ sr yr. 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. The 27 UHECR detected by Auger are distributed in the range $\delta \in [-61, 9.6]$ (or at galactic latitudes $b \in [-78.6, 54.1]$ – open circles in Figs 1 and 2).

### 2.2 HIPASS catalogue

We compare the arrival directions of Auger UHECRs with the locations of sources of the HI Parkes All-Sky Survey (HIPASS – Meyer et al. 2004). This is a blind survey of sources in H I covering the full southern sky at $\delta < 25^\circ$ which is the same sky area accessed by the Auger observatory. The full catalogue is composed by a list of 4315 sources at $\delta < 2^\circ$ (HICAT – Meyer et al. 2004; Zwaan et al. 2004) and by extension to the northern sky up to $\delta = 25^\circ$ (NHICAT – Wong et al. 2006) which includes 1002 sources. All sources are shown in Fig. 1 with the 27 UHECR detected by Auger.

The HICAT and NHICAT have different level of completeness. To have a catalogue complete in flux at the 95 per cent level, we cut the HICAT at $S_{\text{tot}} > 7.4$ Jy km s$^{-1}$ and the NHICAT at $S_{\text{tot}} > 15$ Jy km s$^{-1}$ as discussed in Zwaan et al. (2004) and Wong et al. (2006). $S_{\text{tot}}$ represents the total H I line flux. For the purposes of this Letter, we also considered the H I sources within 100 Mpc which is the maximum distance at which UHECRs of $E > 57$ EeV can survive the Greisen–Zatsepin–Kuzmin (GZK) suppression effect (see e.g. Harari, Mollerach & Roulet 2006). We can call this sample 95HIPASS: it contains 2414 sources from the HICAT and 290 sources from the NHICAT for a total of 2704 sources and covers the entire sky at $\delta < 25^\circ$. We will also consider the southern sky sample alone which is more complete and can be cut at 99 per cent completeness for $S_{\text{tot}} > 9.4$ Jy km s$^{-1}$ (also by considering sources at $< 100$ Mpc). This sample contains 1946 sources and is called 99HICAT.

## 3 ANALYSIS

To quantify the possible correlation between UHECR Auger events and the distribution of H I local galaxies, we use the method adopted by George et al. (2008). In order to quantify the probability that two sets of sources are drawn from the same parent population of objects, we perform the two-dimensional generalization of the Kolmogorov–Smirnov (KS) test (Peacock 1983) proposed by Fasano & Franceschini (1987).

In our case, the test is used to compare two data samples, i.e. the UHECR and the H I galaxies. This test can then measure either if UHECRs have a galaxy counterpart and, vice versa, if a concentration of galaxies has an UHECR counterpart. The test relies on the statistic $D$, also used for the unidimensional KS test, which represents the maximum difference between the cumulative distributions of the two data samples. For each UHECR data point $j_i$, we compute a set of four numbers $d_{j,i}$ ($i = [1, 4]$) defined as the difference of the relative fraction of UHECR and H I galaxies found in the four natural quadrants defined around point $j$. Hence, $D = \max(d_{j,i})$ for all the data points considered. Defining $Z_D = D\sqrt{n}$, the strength of the correlation between two catalogues is the integral probability distribution $P(D\sqrt{n} > \text{observed})$, 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.

The probability can be computed analytically for large data sets ($n > 80$ – Fasano & Franceschini 1987). In our case, having only 27 UHECR, we have to rely on Monte Carlo simulations. We generate a large set of random UHECR events according to the relative Auger exposure. For each synthetic UHECR sample, we compute $Z_D$ by correlating it with the catalogue of H I galaxies. The probability of...
the observed $Z_{\eta}$ is given by the number of times we find a value of $Z_{\eta}$ larger than the observed one. This is the probability that the correlation between the (real) UHECR sample and the H I galaxies is not by chance. Large (low) values of the probability indicate a good (poor) correlation between the Auger UHECRs and the given H I galaxy sample.

As noted by George et al. (2008), the two-dimensional KS test can be performed with the number of data points or with the flux of the sources in the comparison sample. In our case, $D$ represents the maximum difference between the number of UHECRs and that of the sum of the galaxies weighted for their flux and for the relative Auger exposure. The advantage of using the weighted flux of the sources is that it accounts for their distance. George et al. (2008) found that the UHECRs are more correlated with the weighted flux of Swift AGN than with their position. In Fig. 2, we show the map of the flux of the HIPASS catalogue weighted for the Auger relative exposure.

4 RESULTS

We found that with the 95HIPASS catalogue (2704 H I sources complete in flux at 95 per cent) the probability that UHECRs are correlated with H I galaxies is 71.6 per cent by using the weighted flux of the H I sources. Considering the more complete 99HICAT (1946 H I sources complete in flux at 99 per cent) distributed within 100 Mpc and the 25 UHECRs distributed in the same sky region, we find a larger flux-weighted probability of 87.8 per cent. This probability is slightly smaller than found with local AGN by George et al. (2008).

However, having a large sample of H I galaxies we can study if the correlation probability changes by considering different subsamples of galaxies selected according to their distance or luminosity. We have considered four bins of distance with an equal number of sources (~500) per bin. The correlation probability shows a maximum of 95 per cent (97.8 per cent for the 99HICAT) for sources distributed between 37.8 and 55 Mpc. We show these results in Fig. 3 (open circles and stars in the bottom panel).

Similarly, we defined four equally populated luminosity bins, or, equivalently, four bins of H I mass content, since we can use $M/M_\odot = 2.36 \times 10^7 D_{\odot}^2 S_{\text{int}}$, to estimate the H I mass (here, $S_{\text{int}}$ is measured in Jy km s$^{-1}$). We find that the probability (left-hand panel in Fig. 3) is maximized by the most H I luminous or massive (in H I) sources (98 and 99 per cent for the 95HIPASS and 99HICAT sample, respectively, for $M > 1.1 \times 10^{10} M_\odot$).

Selecting those H I galaxies located within two $20^\circ \times 20^\circ$ boxes centred on the radio galaxies Cen A and M87 (green boxes in Fig. 1), we can show where they lie in the luminosity–distance plane in Fig. 3 (orange and green dots, respectively). While there is no clustering of points at the distances of Cen A and Virgo, we can see that H I galaxies in the direction of Cen A do cluster at distances of 40–50 Mpc, where the Centaurus cluster is. This could explain why some UHECR events appear to be associated with the radio galaxy Cen A, and none with M87: beyond Cen A, there is the Centaurus cluster, richer of H I emitting spirals than the Virgo cluster. The ratio of the integrated H I fluxes from the two $20^\circ \times 20^\circ$ boxes (Virgo/Cen A) is 5.9. To this, we have to multiply by another factor of 3 for the lower Auger exposure in the direction of Virgo.

The sample has too few galaxies beyond 100 Mpc to test the GZK effect (that would be revealed by finding no correlation for these galaxies).

5 DISCUSSION

The 27 Auger events above 57 EeV, with a total exposure of 9000 km$^2$ sr yr, correspond to an integrated flux, in CGS units:

$$F_\lambda(E > 57\text{ EeV}) \sim 1.1 \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}. \quad (1)$$

This flux is smaller than the electromagnetic flux that we receive from nearby radio-quiet AGN in hard X-rays (see e.g. Tueller et al. 2008). We now compare this flux with the expected flux of other candidate sources. We will consider flaring or bursting sources, that are impulsive events, but the spreading of the arrival times of UHECRs from a source located at a distance $D$, $\Delta t \sim D^2/2c$, due to even tiny magnetic deflections, ensure that we can treat all candidate sources as continuous. We will estimate the predicted flux in two different ways.

First, assume that a class of sources is characterized by a pulse of emission of UHECRs, of average total energy $\langle E \rangle$. Assume also that these events occur at a rate $\langle R \rangle$ per galaxy, per year, and consider those events occurring within the GZK radius $D_c$. We have

$$F = \langle R \rangle \frac{\langle E \rangle}{3.15 \times 10^7} \frac{N_g(D < D_c)}{4\pi(\alpha D_c)^2}, \quad (2)$$

where $3.15 \times 10^7$ is the number of seconds in 1 yr and $N_g(D < D_c)$ is the number of galaxies within $D_c$ of $L_g$ luminosity. The average distance of the sources is $aD_c (a = 3/4$ for sources homogeneously distributed). Setting the mean local galaxy density $n_g = N_g/(4\pi D_c^2/3) = 10^{-2} n_{g, -2}$ Mpc$^{-3}$, we have

$$F \sim 1.2 \times 10^{-57} \langle E \rangle R n_{g, -2} \frac{D_{100}}{a^2} \text{ erg cm}^{-2} \text{s}^{-1}, \quad (3)$$

where $D_c = 100 D_{100}$ Mpc.

The second estimate on the predicted UHECR flux uses the electromagnetic flux as a proxy. Assume that we detect, for a typical member of a class of sources, an average fluence $\langle F \rangle$, and that there are $N$ events per year. If a fraction $\eta$ of these events comes from sources within $D_c$, we have

$$F = \eta \langle F \rangle N \frac{\langle E \rangle}{3.15 \times 10^7}. \quad (4)$$
The required fluence of these sub-energetic nearby long GRBs, to match the UHECRs flux, should be

\[ \langle F \rangle \sim 3.15 \times 10^{-4} \epsilon_{\text{CR}} \frac{F_{\text{Auger}}}{\eta N} \text{ erg cm}^{-2}, \]
where $\epsilon_{\text{CR}}$ is the ratio of the emitted energy in radiation and UHECR. If $n \sim \epsilon_{\text{CR}} \sim 1$, these events constitute a sizeable fraction of the total fluence of all long BATSE GRBs in 1 yr (which is $F \sim 0.024/9 \sim 2.7 \times 10^{-3}$ erg cm$^{-2}$).

Since we know that the large majority of long GRBs are not nearby, newly born magnetars should not constitute conspicuous events in hard X-rays. Their fluence must be mostly emitted in another energy range. GRB 060218 (Campana et al. 2006) with an energy of a few $10^{50}$ erg, at a distance of 145 Mpc, could be one of these events, and Soderberg et al. (2006) and Toma et al. (2007) already suggested that this GRB was powered by a newly born magnetar. The spectrum of its prompt emission peaked at $\sim 5$ keV, i.e. its fluence in relatively soft X-rays exceeded the 15–150 keV fluence. It was also very long, slowly rising, and would not have been detected by BATSE. Soderberg et al. (2006) pointed out that these sub-energetic long GRBs should not be strongly beamed (not to exceed the rate of type Ib and Ic supernovae), and should occur at a rate of $230_{-90}^{+490}$ Gpc$^{-3}$ yr$^{-1}$, corresponding to $R \approx 10^{-4}$ events per $L_*$ galaxy per year, about 10 times larger than for classical long GRBs whose radiation is collimated into 1 per cent of the sky. According to this rate, equation (3) would then demand $(E) \sim 6 \times 10^{50}$ erg in UHECRs to match the observed flux.

6 CONCLUSION

We have correlated the cosmic rays with $E > 57$ EeV detected by the Auger observatory with a complete, absorption-free sample of HI selected galaxies. We found a significant correlation when correlating the HI flux of galaxies of our sample.

When considering the largest 95HIPASS catalogue and the 27 UHECRs we find a weak correlation (probability of 72 per cent), while a larger significance (87.8 per cent) is reached if we consider the most complete 99HICAT sample of galaxies (though with 25 UHECRs). These probabilities are maximized by cutting the HI sample in distance or luminosity bins: it becomes 99 per cent when considering the 500 most luminous (or most HI massive) galaxies (one-fourth of the sample), and 98 per cent when considering the 500 galaxies lying between 38 and 54 Mpc, where the Centaurus cluster of galaxies is.

Thus, there is the possibility that the UHECRs coming from the direction of Cen A are instead coming from the more distant Centaurus cluster. Galaxies of this cluster are richer in HI than Virgo galaxies, explaining why there is no UHECR event from the direction of Virgo.

This sample is formed by HI emitting galaxies, therefore it is biased against ellipticals. The found correlation with these galaxies, per se, is not disproving the found correlation with AGN (Abraham et al. 2007, 2008; George et al. 2008), since they also trace the local distribution of matter, as spiral galaxies do. On the other hand, it opens up the possibility, on equal foot, that UHECRs are produced by GRBs or newly born magnetars (see also Singh, Ma & Arons 2004 who used AGASA events). With the caveat that it is premature, with so few events and big theoretical uncertainties, to draw strong conclusions, we have pointed out that although classical (i.e. energetic) long and short GRBs have difficulties in producing the required UHECR flux, newly born magnetars can. If so, they could also be a subclass of long GRBs, possibly sub-energetic and relatively nearby, powered by fastly spinning, newly born magnetars. The future increased statistics of UHECRs arrival directions will help to discriminate among the different proposed progenitors, especially if there will be (or not) an excess of events close to the radio core and/or lobes of Cen A.

ACKNOWLEDGMENTS

We thank the referee for constructive comments. We thank the ASI I/088/06/0 and the 2007 PRIN–INAF grants, and Ivy Wong and Martin Zwaan for providing the NHICAT catalogue. The Parkes telescope is a part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

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