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Centaurus A as a source of ultra high energy cosmic rays

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ABSTRACT
The propagation of ultra high energy cosmic rays in Galactic and extragalactic magnetic fields is investigated in the present paper. The motion of charged particles of different energies and chemical composition is simulated using different Galactic magnetic field models. Positions for the real sources of events registered at the Auger Observatory are calculated taking into account the influence of both Galactic and extragalactic turbulent fields. The possibility of their correlation with the Centaurus A radio galaxy is analysed.

Keywords: Ultra-high energy cosmic rays – cosmic magnetic fields – propagation of UHECRs

1 INTRODUCTION

Cosmic rays (CR) are known as fluxes of high-energy subatomic particles, photons or neutrino generating extended atmospheric showers of secondary particles that interact with molecules of nitrogen and oxygen which are prevalent in the Earth atmosphere's upper strata. CR possessing the energy $E > 10^{19}$ eV arrive at the Earth with the interval of less than one event per year over 1 km^2 in π steradian (i.e. with the energy flux of 30 eV/cm^2/sec) (Greisen, 1966).

Ultra high energy cosmic rays (UHECR) are believed to be of extra-galactic origin due to the absence of sources powerful enough to provide their sufficient acceleration within our Galaxy as well as due to almost isotropic large-scale distribution of CR along the lines of their entering the atmosphere (The Pierre Auger Collaboration: J. Abraham et al., 2009). The hypothesis concerning UHECR's astrophysical nature is also supported by registering the Greisen–Zatsepin–Kuzmin (GZK) effect (Greisen, 1966) in the HiRes experiment (Abbasi et al., 2008), as well as in observations carried out at the Auger observatory (Abraham et al., 2008).

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The correlation between CR and galaxies from the active galactic nuclei (AGN) Veron-Cetti-Veron (VCV) catalogue (Véron-Cetty and Véron, 2010) can be accepted as a possible explanation of UHECR's nature, provided their origin is extragalactic while their horizon is energy dependent which agrees with the data on GZK-cutoff.

According to the analysis of the refreshed data from the Auger observatory (Abreu et al., 2010), the registered UHECR's correlation with the galaxies from the VCV catalogue has diminished from level $3\,\sigma$ to $2\,\sigma$ compared to the previous version of data update. As the result only 30 % of UHECR potentially correlate with the directions towards AGN whereas the rest manifest the signs of isotropic distribution. The only exception is the neighbourhood of the closest to the Earth active galaxy Centaurus A where the registered set of ultra energy events appeared to be a lot more volumetric than it could be statistically correct to expect.

In this paper we verify the possibility of the observed in the area of Centaurus A events being UHECR accelerated in this galaxy. Therefore we solve the reversed task by modelling CR's trajectory on the basis of present data from Auger observatory. The model takes into account the influence of Galactic and extragalactic magnetic fields as well as the CR chemical composition.

2 MODELING

Magnetic field distorts the CR's charged particles trajectory via Lorenz force. If the field is static it does not affect the particle's energy. Considering the fact that typical values of CR energy far exceed the particles' rest energy we assume that they spread with velocity close to the speed of light. In this case the equations describing the motion of ultra-relativistic particles in the magnetic field $B(r)$ are:

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{qc^2}{E}[v \times B]\,, \quad \frac{\mathrm{d}r}{\mathrm{d}t} = v\,, \tag{1}$$

where q is particle's charge, E – its energy, provided the Lorenz factor $\gamma \gg 1$ and velocity v.

3 MAGNETIC FIELDS

Modelling the motion of UHECR we considered influence of Galactic as well as extragalactic magnetic fields. Galactic magnetic field consists of regular and random components. The regular component's structure is believed to generally follow the matter's distribution in the Galaxy (Han, 2009). Nowadays the source and structure of extragalactic magnetic field are not exactly clear. Thus while solving specific tasks it is defined as having random structure (Beck, 2001).

3.1 Galactic magnetic field

Regular component. There are several models describing regular Galactic magnetic field (Sutherland et al., 2010). They differ in both parameters' numeric values and presence and structure of the field's components. The regular component of Galactic magnetic field is rather conveniently described via the spiral structure of 2π-symmetry (axisymmetric spiral

(ASS)) or π-symmetry (bisymmetric spiral (BSS)) (Stanev, 1997). In our research we have applied the most recent models (Prouza and Šmída, 2003), (Kachelrieß et al., 2007) and (Pshirkov et al., 2011). They present the magnetic field as a superposition of the disc component and the field of Galactic halo. In (Prouza and Šmída, 2003) and (Kachelrieß et al., 2007) BSS symmetry is used for describing the disc field whereas in (Pshirkov et al., 2011) both ASS and BSS disc field's symmetry types are considered (henceforth we treat them off as different models).

The disc field comprises radial and azimuth components which are set in cylindrical coordinates in the disc's area by expressions

$$B_r = B(r,\theta)\sin(p)\,, \quad B_\theta = B(r,\theta)\cos(p)\,, \tag{2}$$

where pitch angle p is the angle between the magnetic vector at a certain point and the normal to radius-vector $\mathbf{r}$ in this point.

The function $B(r,\theta)$ is set by the equation of logarithm spiral:

$$B(r,\theta) = B(r)\cos\left[\theta - \frac{1}{\tan p}\ln\left(\frac{r}{\xi_0}\right)\right], \tag{3}$$

or

$$B(r,\theta) = B(r)\cos\left[\theta - \frac{1}{\tan p}\ln\left(\frac{r}{R_8}\right) + \varphi\right]. \tag{4}$$

Parameters in formulae (3) and (4) are set by expressions

$$\varphi = \frac{1}{\tan p}\ln\left(1 + \frac{d}{R_8}\right) - \frac{\pi}{2},\ \xi_0 = (R_8 + d)\exp\left(-\frac{\pi}{2}\tan p\right)\,, \tag{5}$$

where $R_8 = 8.5$ kpc is the distance from the Galactic center to the Solar system, d is the distance from the Solar system to the closest field's inversion point.

The function of the radial profile $B(r)$ is set by

$$B(r) = \begin{cases} B_8\dfrac{R_8}{r\cos\varphi} = B_0\dfrac{R_8}{r} & r > R_\mathrm{C}\,, \\[2ex] B_8\dfrac{R_8}{R_\mathrm{C}\cos\varphi} = B_0\dfrac{R_8}{R_\mathrm{C}} & r < R_\mathrm{C}\,, \end{cases} \tag{6}$$

where R_8 is local field near the Solar system.

The vertical profile of the disc field above the Galactic plane and under it is considered exponentially decreasing:

$$B(r,\theta,z) = B(r,\theta)\exp\left(-\frac{|z|}{z_0}\right)\,. \tag{7}$$

In models (Prouza and Šmída, 2003) and (Kachelrieß et al., 2007) the field of Galactic halo comprises poloidal and toroidal components while model (Pshirkov et al., 2011) contains the toroidal component only. For the description of the toroidal field we use the model of discs located above and under the Galactic plane. The toroidal field's parameters are set by expressions

$$B_x = -B_T \operatorname{sign}(z) \left[1 + \left(\frac{|z| - h}{w} \right)^2 \right]^{-1} \cos\theta \,, \tag{8}$$

$$B_y = B_T \operatorname{sign}(z) \left[1 + \left(\frac{|z| - h}{w} \right)^2 \right]^{-1} \sin\theta \,, \tag{9}$$

where h is the height of discs above and under the Galactic plane, ω is half-width of Lorenz distribution.

The function B_T in model (Prouza and Šmída, 2003) is given by the following expression

$$B_T = B_{T\max} \left[\Theta(R_T - r) + \Theta(r - R_T) \exp\left(-\frac{r}{R_T} \right) \right] , \tag{10}$$

while in model (Kachelrieß et al., 2007)

$$B_T = B_{T\max} \left[\Theta(R_T - r) + \Theta(r - R_T) \exp\left(-\frac{R_T - r}{R_T} \right) \right] , \tag{11}$$

where Θ is Heaviside function, R_T is toroid's characteristic radius.

In model (Pshirkov et al., 2011)

$$B_T = B_{T\max} \frac{r}{R_T} \exp\left(\frac{R_T - r}{R_T} \right) . \tag{12}$$

The field's dipole component is described by standard equations:

$$B_x = -3\mu_G \cos\phi \sin\phi \sin\theta / \rho^3 \,, \tag{13}$$

$$B_y = -3\mu_G \cos\phi \sin\phi \cos\theta / \rho^3 \,, \tag{14}$$

$$B_z = \mu_G (1 - \cos^2\phi) / \rho^3 \,, \tag{15}$$

where $\rho = \sqrt{r^2 + z^2}$, $\cos\phi = z/\rho$, $\sin\phi = r/\rho$, μ_G is the magnetic dipole momentum.

Random component. It is assumed (Pierre Auger Collaboration et al., 2012) that Galactic magnetic field's random component's impact primarily results into widening the range of UHECR's possible arrival directions relative to the direction defined by the deflection of the trajectory in the regular field. In this case the real location of CR's source is not explicated. Furthermore, under certain conditions the so called "lensing effect" in the magnetic field may occur and generate several images of CR's source (Giacinti et al., 2011a). Yet studying this kind of impact may be fruitful for exploring the properties of Galactic magnetic field and CR's propagation.

CR's ultra high energy is marked by the value of Larmor radius that by far exceeds the length of field's coherence l_0, the latter understood as the distance at which the field's random re-orientation occurs. Thus to estimate the effect caused by the random magnetic field it is sufficient to consider two parameters: l_0 and field's magnitude B_{rms} (Giacinti et al., 2010). The field B_{rms} is characterized by exponentially decreasing vertical profile $R_{\text{rms}} = B_0 \exp(-|z|/z_0)$ (Giacinti et al., 2011b).

According to the observation data Galactic magnetic field's random component is commensurable to the regular one (Prouza and Šmída, 2003). In this paper we employ the values $l_0 = 50$ pc, $B_0 = 4\,\mu$G, $z_0 = 3$ kpc (Giacinti et al., 2011a).

CR deflection ϑ in the random magnetic field on the covered distance L is set by the following expression (Berezinsky et al., 2004)

$$\langle \vartheta^2 \rangle = \frac{2}{9} \left(\frac{Ze}{E} c \right)^2 \langle B^2 \rangle L\, l_0\,, \tag{16}$$

where Ze is particle's charge, E is its energy.

The distance covered by UHECR (those registered by the Earth-located detectors) in the Galactic turbulent field can be estimated as

$$L_{\text{gal}} = \min \left(\frac{z_0}{\sin b_{\text{G}}}\, ;\; L_{\max} = 20\,\text{kpc} \right)\,, \tag{17}$$

where b_{G} is Galactic latitude of CR's arrival direction. Thus we acquire the value of CR's final deflection

$$\vartheta = 22^\circ\, Z \left(\frac{L_{\text{gal}}}{1\,\text{kpc}} \right)^{1/2} \left(\frac{E}{10^{18}\,\text{eV}} \right)^{-1}\,. \tag{18}$$

3.2 Extragalactic magnetic field

There are structures in the Universe comprising clusters of galaxies, filaments, layers of increased density and voids with low density. It is assumed that in entities of this kind magnetic field is boosted due to the formation of large scale structures. Diverse numeric modelling of the said process demonstrates correspondence extragalactic magnetic field's distribution with that of matter (Sigl et al., 2004). Astrophysical objects, UHECR's sources in particular, are normally located within the structured areas. Thus these magnetic structures as well as the Galactic magnetic field necessarily impact the propagation of CR. The structured extragalactic magnetic field influences both CR's deflection and the time of their reaching the observer.

According to the recent research of the gamma-ray range, extragalactic magnetic field possesses the value of approximately 10^{-15} G in the voids (Ando and Kusenko, 2010). Although this estimation is rather contradictory; the prior estimation of magnetic field's lower limit being 10^{-17}–10^{-15} G (Taylor et al., 2011). In the suggested calculations we employ the simplest model in which space is divided into cubic cells of size l_{c}. The field is considered uniform within one cell while its direction varies randomly in between the cells. To limit the size of field B we used the value resulting from observation data concerning distant objects polarization plane's Faraday's rotation (Kronberg, 1994) $\langle B \rangle \sqrt{l_0} \leq 10^{-9}$ G Mpc$^{1/2}$, where l_0 is magnetic field's coherence length. Generally l_0 does not equal l_{c} strictly, though this difference is not significant for estimating UHECR's propagation in extragalactic magnetic field. For random extragalactic magnetic field like in the case of Galactic magnetic field's random component, CR's deflection is calculated through formula (16).

Table 1. "CR – Cen A" correlation. Magnetic field components: RG – regular Galactic, RRG – regular + random Galactic, RRGE – regular + random Galactic + extragalactic.

Energy, EeV	CR's chemical composition for different models					
	(Prouza and Šmída, 2003)			(Kachelrieß et al., 2007)		
	RG	RRG	RRGE	RG	RRG	RRGE
142	Mg	Mg-Ar	Ne-Ca	–	Ca-Fe	S-Fe
79	He	He-Li	p-Be	He-Li	He-C	He-N
77	N-O	C-Ne	B-Ne	–	Mg-Ar	Ne-Ar
68	p	p	p-He	p	p-He	p-He
66	–	p	p	p	p	p
61	–	–	–	Ne-Mg	O-S	N-S
Energy, EeV	CR's chemical composition for different models					
	(Pshirkov et al., 2011) – ASS			(Pshirkov et al., 2011) – BSS		
	RG	RRG	RRGE	RG	RRG	RRGE
68	p	p	p	–	–	p
66	p	p	p	–	–	p

Considering the limitations over the value of extragalactic magnetic field we acquire numeric values of deflection for CR with energy E and charge Z, located at the distance L_0 from random sources:

$$\vartheta = 25^\circ\, Z \left(\frac{L_0}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{E}{10^{18}\,\mathrm{eV}}\right)^{-1} . \tag{19}$$

4 CENTAURUS A

The Auger observatory registered a set of UHECR in the region of Centaurus A galaxy which is the closest to the Solar system active one. The origin of the registered CR is most likely affiliated with the said galaxy (Abreu et al., 2010). We have modelled the CR's motion in the magnetic field using the above-described methodology.

Figure 1 demonstrates the results of calculations carried out on the basis of various models of the regular Galactic magnetic field. Circles with figures denote the set of events registered by the Auger facility. Circles with the chemical elements symbols correspond to the calculated locations of UHECR's sources for the indicated particle types. Radii of all circles reflect the Auger detectors' experiment error within the confidence interval of 1 σ. Results depicted in Fig. 1a were obtained via the use of model (Prouza and Šmída, 2003); those in Fig. 1b were achieved as the result of using model (Kachelrieß et al., 2007). The figures also demonstrate the outline of Centaurus A radiation areas. These areas are known to have conditions for accelerating CR up to ultra high energies (Rieger and Aharonian, 2009). Overlapping of the circles corresponding to the calculated sources' location and the image of Centaurus A was chosen as the criterion for defining the correlation of the analysed events and the said galaxy.

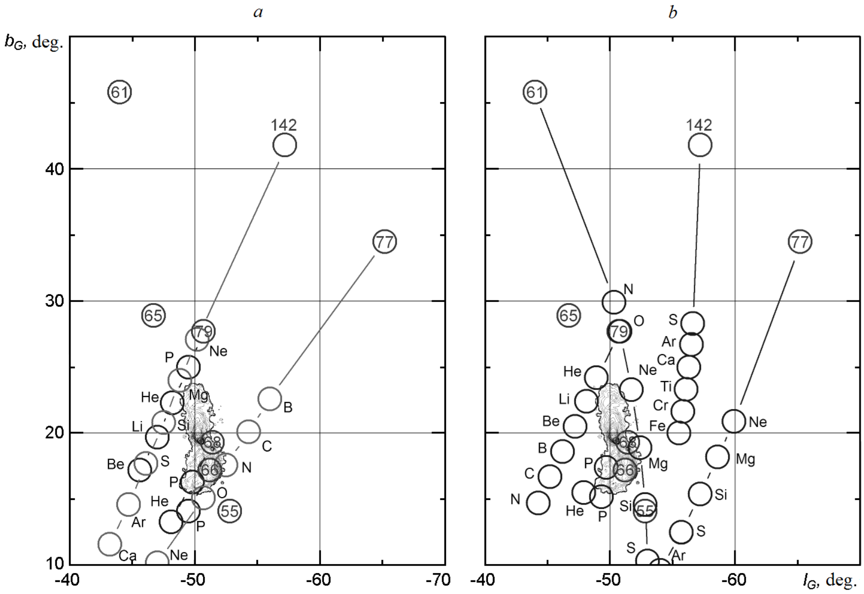

Figure 1. Source positions for different models of regular Galactic magnetic field: a – (Prouza and Šmída, 2003), b – (Kronberg, 1994).

Considering the Galactic field's random component as well as the extragalactic field, Eqs. (18) and (19) can lead to widening the area of the source's possible localization from few degrees (for light elements) up to 10°–15° (for heavy elements), but without actually changing its location.

We have found out that out of all CR coming from Centaurus A area only six can in fact originate in this galaxy – those with the energy of 61, 66, 68, 77, 79 and 142 EeV. Table 1 demonstrates chemical composition of the particles with the indicated energy. These particles correlate with Centaurus A following the two chosen models of the Galactic field and considering the impact of the magnetic field's various components.

5 CONCLUSIONS

Centaurus A may be the source of the events in its nearby region registered by the Auger observatory. Models (Prouza and Šmída, 2003) and (Kachelrieß et al., 2007) provide similar results. According to the calculations carried out on the basis of model (Prouza and Šmída, 2003) five events correlate with Centaurus A. When model (Kachelrieß et al., 2007) is employed six such events correlate with Centaurus A. The common tendency of shifting CR's chemical composition towards heavier nuclei at the boost of energy of the corresponding event is noted in all cases of possible correlation with the object under investigation. It is relevant for both models.

REFERENCES

Abbasi, R. U., Abu-Zayyad, T., Allen, M., Amman, J. F., Archbold, G., Belov, K., Belz, J. W., Ben Zvi, S. Y., Bergman, D. R., Blake, S. A., Brusova, O. A., Burt, G. W., Cannon, C., Cao, Z., Connolly, B. C., Deng, W., Fedorova, Y., Finley, C. B., Gray, R. C., Hanlon, W. F., Hoffman, C. M., Holzscheiter, M. H., Hughes, G., Hüntemeyer, P., Jones, B. F., Jui, C. C. H., Kim, K., Kirn, M. A., Loh, E. C., Maestas, M. M., Manago, N., Marek, L. J., Martens, K., Matthews, J. A. J., Matthews, J. N., Moore, S. A., O'Neill, A., Painter, C. A., Perera, L., Reil, K., Riehle, R., Roberts, M., Rodriguez, D., Sasaki, N., Schnetzer, S. R., Scott, L. M., Sinnis, G., Smith, J. D., Sokolsky, P., Song, C., Springer, R. W., Stokes, B. T., Thomas, S. B., Thomas, J. R., Thomson, G. B., Tupa, D., Westerhoff, S., Wiencke, L. R., Zhang, X. and Zech, A. (2008), First Observation of the Greisen-Zatsepin-Kuzmin Suppression, *Phys. Rev. Lett.*, **100**(10), 101101, arXiv: `astro-ph/0703099`.

Abraham, J., Abreu, P., Aglietta, M., Aguirre, C., Allard, D., Allekotte, I., Allen, J., Allison, P., Alvarez-Muñiz, J., Ambrosio, M. and et al. (2008), Observation of the Suppression of the Flux of Cosmic Rays above 4×10^{19} eV, *Phys. Rev. Lett.*, **101**(6), 061101, arXiv: `0806.4302`.

Abreu, P., Aglietta, M., Ahn, E. J., Allard, D., Allekotte, I., Allen, J., Alvarez Castillo, J., Alvarez-Muñiz, J., Ambrosio, M., Aminaei, A. and et al. (2010), Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter, *Astroparticle Physics*, **34**, pp. 314–326, arXiv: `1009.1855`.

Ando, S. and Kusenko, A. (2010), Evidence for Gamma-ray Halos Around Active Galactic Nuclei and the First Measurement of Intergalactic Magnetic Fields, *Astrophys. J. Lett.*, **722**, pp. L39–L44, arXiv: `1005.1924`.

Beck, R. (2001), Galactic and Extragalactic Magnetic Fields, *Space Science Reviews*, **99**, pp. 243–260, arXiv: `astro-ph/0012402`.

Berezinsky, V. S., Grigorieva, S. I. and Hnatyk, B. I. (2004), Extragalactic UHE proton spectrum and prediction for iron-nuclei flux at 10^{8}-10^{9} GeV, *Astroparticle Physics*, **21**, pp. 617–625, arXiv: `astro-ph/0403477`.

Giacinti, G., Derkx, X. and Semikoz, D. V. (2010), Search for single sources of ultra high energy cosmic rays on the sky, *Journal of Cosmology and Astroparticle Physics*, **3**, 022, arXiv: `0907.1035`.

Giacinti, G., Kachelrieß, M., Semikoz, D. V. and Sigl, G. (2011a), Propagation of Ultrahigh Energy Nuclei in the Magnetic Field of our Galaxy, *International Cosmic Ray Conference*, **2**, p. 43.

Giacinti, G., Kachelrieß, M., Semikoz, D. V. and Sigl, G. (2011b), Ultrahigh energy nuclei in the turbulent Galactic magnetic field, *Astroparticle Physics*, **35**, pp. 192–200, arXiv: `1104.1141`.

Greisen, K. (1966), End to the Cosmic-Ray Spectrum?, *Phys. Rev. Lett.*, **16**, pp. 748–750.

Han, J. (2009), The magnetic structure of our Galaxy: a review of observations, in K. G. Strassmeier, A. G. Kosovichev and J. E. Beckman, editors, *IAU Symposium*, volume 259 of *IAU Symposium*, pp. 455–466, arXiv: `0901.1165`.

Kachelrieß, M., Serpico, P. D. and Teshima, M. (2007), The Galactic magnetic field as spectrograph for ultra-high energy cosmic rays, *Astroparticle Physics*, **26**, pp. 378–386, arXiv: `astro-ph/0510444`.

Kronberg, P. P. (1994), Extragalactic magnetic fields, *Reports on Progress in Physics*, **57**, pp. 325–382.

Pierre Auger Collaboration, Abreu, P., Aglietta, M., Ahn, E. J., Albuquerque, I. F. M., Allard, D., Allekotte, I., Allen, J., Allison, P., Alvarez Castillo, J. and et al. (2012), Search for signatures of magnetically-induced alignment in the arrival directions measured by the Pierre Auger Observatory, *Astroparticle Physics*, **35**, pp. 354–361, arXiv: `1111.2472`.

Prouza, M. and Šmída, R. (2003), The Galactic magnetic field and propagation of ultra-high energy cosmic rays, *Astronomy and Astrophysics*, **410**, pp. 1–10, arXiv: `astro-ph/0307165`.

Pshirkov, M. S., Tinyakov, P. G., Kronberg, P. P. and Newton-McGee, K. J. (2011), Deriving the Global Structure of the Galactic Magnetic Field from Faraday Rotation Measures of Extragalactic Sources, *Astrophys. J.*, **738**, 192, arXiv: 1103.0814.

Rieger, F. M. and Aharonian, F. A. (2009), Centaurus A as TeV γ-ray and possible UHE cosmic-ray source, *Astronomy and Astrophysics*, **506**, pp. L41–L44, arXiv: 0910.2327.

Sigl, G., Miniati, F. and Enßlin, T. A. (2004), Ultrahigh energy cosmic ray probes of large scale structure and magnetic fields, *Phys. Rev. D*, **70**(4), 043007, arXiv: astro-ph/0401084.

Stanev, T. (1997), Ultra-high-energy Cosmic Rays and the Large-scale Structure of the Galactic Magnetic Field, *Astrophys. J.*, **479**, pp. 290–295, arXiv: astro-ph/9607086.

Sutherland, M. S., Baughman, B. M. and Beatty, J. J. (2010), CRT: A numerical tool for propagating ultra-high energy cosmic rays through Galactic magnetic field models, *Astroparticle Physics*, **34**, pp. 198–204, arXiv: 1010.3172.

Taylor, A. M., Vovk, I. and Neronov, A. (2011), Extragalactic magnetic fields constraints from simultaneous GeV-TeV observations of blazars, *Astronomy and Astrophysics*, **529**, A144, arXiv: 1101.0932.

The Pierre Auger Collaboration: J. Abraham, Abreu, P., Aglietta, M., Aguirre, C., Ahn, E. J., Allard, D., Allekotte, I., Allen, J., Alvarez-Muñiz, J., Ambrosio, M. and et al. (2009), Astrophysical Sources of Cosmic Rays and Related Measurements with the Pierre Auger Observatory, *ArXiv e-prints*, arXiv: 0906.2347.

Véron-Cetty, M.-P. and Véron, P. (2010), A catalogue of quasars and active nuclei: 13th edition, *Astronomy and Astrophysics*, **518**, A10.