Magnetic Fields of Nearby Active Galactic Nuclei and Correlation of the Highest-Energy Cosmic Rays with their Positions

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November 20, 2008

Abstract

The correlation between the pointing direction of ultra high energy cosmic rays and AGN observed by the Pierre Auger Collaboration is explained in the framework of acceleration process in AGN. This acceleration process is produced by a rotating accretion disk around a black hole that is frozen-in magnetic field. In a result the accretion disk is acting as a induction accelerator of cosmic rays. We estimate the resulting magnetic field in the framework of the magnetic coupling process. The results of our calculations allow to make the conclusion that the Flat Spectrum Radio Quasars appear the effective cosmic accelerators. We estimate also the attenuation of highest-energy cosmic rays in a result of their interaction with ambient radiation field.

Key words: quasars, accretion disks, magnetic fields, cosmic rays.

1 Introduction

Recently, using data collected at the Pierre Auger observatory during the past 3.7 years, the Pierre Auger Collaboration [(The Pierre Auger Collaboration, 2007a,b)] have demonstrated a correlation between the arrival directions of cosmic rays with energy above $\sim 6 \times 10^{19}$ eV and the positions of active galactic nuclei (AGNs) lying at a distance less than $\sim 75$ Mpc. A confidence level of anisotropy have been at value of more than 99% through a number of special tests [(The Pierre Auger Collaboration, 2007b)]. The authors claimed that the observed correlation is compatible with the hypothesis that cosmic rays with the highest energies originate from extra-galactic sources located quite close because their flux is not significantly attenuated by the Greisen-Zatsepin-Kuz’min effect, i.e. by interaction with the cosmic background radiation. Though the present data can’t identify AGN as the sources of cosmic rays unambiguously, AGNs or objects having a similar spatial distribution can be considered as possible sources. Certainly, these present data do not identify as the sources of cosmic rays unambiguously. Therefore, other candidate sources which are distributed as nearby AGN can’t be excluded. Thus, Dermer (2007) has considered gamma ray bursts and only blazar AGN as the sources of UHECRs. More original idea has been suggested by Grib & Pavlov (2007). They suggested the hypothesis that dark matter consist of superheavy particles with the mass close to the Grand Unification scale. They claimed that some part of these particles, which were created from vacuum by the gravitation of the expanding Universe, can be swallowed by the supermassive black holes and can decay on visible particles producing the flow of UHECRs observed by the Auger group.

The interesting look on AGNs as cosmic supercolliders has been developed by Kardashev and his colleagues [Kardashev, 1995; Shatsky, 2003; Shatsky & Kardashev, 2002, 2006]. They considered the structure and magnitude of electromagnetic field produced by a rotating accretion disk around a black hole. The accretion disk was modeled as a torus filled with plasma and the frozen-in magnetic field. It acts as an induction accelerator of cosmic rays along the axis of an accretion disk.

According to Shatsky (2003) the maximum energy of the accelerated charged particle is represented as

$$E_{\text{max}} \approx 5 \times 10^{11} \left( \frac{\Omega R}{c} \right) \left( \frac{\Omega r_g}{\Omega R} \right) \left( \frac{B}{10^4 G} \right) \left( \frac{M}{M_\odot} \right) \text{eV}$$

where $R$ is the distance from a massive black hole to an accretion torus, $\Omega$ is an angular velocity of a torus, $r_g$ is the gravitational radius and $\Omega_g$ is the angular velocity at $r_g$.

If the basic parameters of the accretion torus near a black hole are of the same order, i.e. $\Omega \sim \Omega_g$ and $R \sim r_g$, the Eq. (1) transforms to

$$E_{\text{max}} = 2.5 \times 10^{10} \left( \frac{B}{10^4 G} \right) \left( \frac{M}{M_\odot} \right) \text{eV}$$

(2)
Another process that can be responsible for generation of ultra high energy cosmic rays has been most recently considered by Koide & Arai (2008). They considered the magnetic reconnection as a basic process of energy extraction from a rotating supermassive black hole. Magnetic reconnection is one of the important processes for the particle acceleration and heating. The relativistic reconnection can be also responsible for generation of ultra high energy cosmic rays. Genuinely this process occurs if the magnetic energy exceeds the plasma energy including its rest energy. And in this case the magnetic field of AGN takes a key role in the process of acceleration and generation of cosmic rays.

The basic goal of our paper is to obtain the real estimation of the magnetic field strength in the close vicinity of accreting supermassive black hole (SMBH) in AGNs and to obtain the more real estimations of $E_{\text{max}}$ from Eq.(2).

2 Magnetic coupling process and determination of magnetic field strengths of supermassive black holes (SMBH)

Recently Li (2002); Wang & Xiao (2002); Wang et al. (2003); Zhang, Lu & Zhang (2005), have studied as a possible mechanism for transferring energy and angular momentum from rotating black hole to its surrounding disk the magnetic coupling process through the closed field lines connecting the Kerr black hole with its accretion disk. This process can be considered as one of the variants of the Blanford-Znajek (BZ) process (Blanford & Znajek, 1977). It is assumed that the disk is stable, perfectly conducting, thin and Keplerian. The magnetic field is assumed to be constant on the black hole horizon and to vary as a power law with the radial coordinate of the accretion disk.

Since the magnetic field on the horizon $B_H$ is brought and held by its surrounding magnetized matter of a disk there must exist some relation between the magnetic field strength and accretion disk and finally the bolometric luminosity of AGN. This relation have been obtained by Gan, Wang & Li (2007). It has a form:

$$B_H = k \frac{(2L_{bol}/\varepsilon c)^{\frac{1}{2}}}{R_H}, \quad k \approx 1$$

(3)

Here $L_{bol} = \varepsilon \dot{M} c^2$, $R_H = \frac{GM}{1 + \sqrt{1 - (a/M)^2}}$, $\dot{M}$ is the accretion rate, $\varepsilon$ is the radiation conversion efficiency (calculated, for example, by Novikov & Thorne (1973); Krolik (2007); Shapiro (2007)). The Eq.(2) is transformed into

$$B_H = 6.2 \times 10^8 \left( \frac{M_{BH}}{M_\odot} \right)^{\frac{1}{2}} \left( \frac{\eta}{\varepsilon} \right)^{\frac{1}{2}} \frac{1}{1 + \sqrt{1 - \left( \frac{a}{M_{BH}} \right)^2}}$$

(4)

where $(a/M_{BH})$ is the Kerr parameter and $\eta = L_{bol}/L_{Edd}$ and $L_{Edd} = 1.3 \times 10^{38}(M_{BH}/M_\odot)$ is the Eddington luminosity.

The relation (4) can be used for estimation $E_{\text{max}}$ from Eq.(2). After substituting Eq.(4) into Eq.(2) one gets:

$$E_{\text{max}} \approx 1.6 \times 10^{15} \left( \frac{M_{BH}}{M_\odot} \right)^{\frac{1}{2}} \left( \frac{\eta}{\varepsilon} \right)^{\frac{1}{2}} \frac{1}{1 + \sqrt{1 - \left( \frac{a}{M_{BH}} \right)^2}}$$

(5)

3 Estimating maximal energy for specific active galactic nuclei (AGN)

We are starting with commonly accepted parameters for accreting Kerr supermassive black holes (SMBHs).

If one chooses for Eq.(5) the next values of physical parameters: $M_{BH} = 10^9 M_\odot$, $\eta \approx 1$, $\varepsilon \approx 0.1$ and $(a/M_{BH}) \approx 1.0$ one gets

$$E_{\text{max}} = 1.6 \times 10^{20} \text{eV}$$

(6)

Below we consider more real situation. A systematic analysis of a large sample of radio-loud AGN available in the BeppoSAX public archive has been performed by Grandi, Malaguti & Fiocchi (2005). Their sample includes AGN of various types: Narrow Line Radio Galaxies (NRLG), Broad Line Radio Galaxies (BLRG), Steep Spectrum Radio Quasars (SSRQ) and Flat Spectrum Radio Quasars (FSRQ) (see Table 6 from their paper).

Our calculations of the maximal energy magnitude for these types of AGN are presented in Tables 1, 2 and 3. One can see from these results that the maximal energy value essentially exceeding the Greisen-Zatsepin-Kuz'min (GZK) cutoff is reached only by FSRQ sources. It is well-known that this class is characterized by the presence of a non-thermal beamed component. It shows also a featureless continuum and a significantly flatter average spectral slope. These facts give evidence that the most effective acceleration process takes place in this type of quasars.
### Table 1: Magnetic field strength.

| Source | $\log\left(\frac{M_{BH}}{M_\odot}\right)$ | $\log\left(\frac{L_{Edd}}{L_{Edd}}\right)$ | $B_H[G]$ | $B_H[G]$ | $B_H[G]$ | $B_H[G]$ | $B_H[G]$ | $B_H[G]$ |
|--------|------------------------------------------|------------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
|        |                                          |                                          | ($\frac{a}{M} = 0.0$) | ($\frac{a}{M} = 0.5$) | ($\frac{a}{M} = 0.9$) | ($\frac{a}{M} = 0.95$) | ($\frac{a}{M} = 0.998$) | ($\frac{a}{M} = 1.0$) |
|        |                                          |                                          | $\varepsilon = 0.057$ | $\varepsilon = 0.081$ | $\varepsilon = 0.16$ | $\varepsilon = 0.19$ | $\varepsilon = 0.32$ | $\varepsilon = 0.42$ |
| BLRG   | 8.64                                    | -1.59                                   | $10^4$     | $9 \times 10^4$     | $8.3 \times 10^4$     | $5.6 \times 10^4$     | $5.3 \times 10^4$     | $5 \times 10^4$     |
| NLRG   | 8.14                                    | -2.92                                   | $3.8 \times 10^3$ | $3.4 \times 10^3$     | $3.2 \times 10^3$     | $3 \times 10^3$     | $2.8 \times 10^3$     |                     |
| SSRQ   | 9.29                                    | -0.90                                   | $10^4$     | $9.4 \times 10^4$     | $8.7 \times 10^4$     | $8.3 \times 10^4$     | $7.7 \times 10^3$     |                     |
| FSRQ   | 9.01                                    | 0.44                                    | $6.7 \times 10^4$ | $6.1 \times 10^4$     | $5.6 \times 10^4$     | $5.6 \times 10^4$     | $5.4 \times 10^4$     | $5 \times 10^4$     |
| Seifert 1 | 7.23                                   | -0.59                                   | $1.6 \times 10^5$ | $1.4 \times 10^5$     | $1.3 \times 10^5$     | $1.3 \times 10^5$     | $1.2 \times 10^5$     |                     |

### Table 2: Maximal energy of cosmic rays.

| Source | $\log\left(\frac{M_{BH}}{M_\odot}\right)$ | $\log\left(\frac{L_{Edd}}{L_{Edd}}\right)$ | $E_{\text{max}}[\text{eV}]$ | $E_{\text{max}}[\text{eV}]$ | $E_{\text{max}}[\text{eV}]$ | $E_{\text{max}}[\text{eV}]$ | $E_{\text{max}}[\text{eV}]$ | $E_{\text{max}}[\text{eV}]$ |
|--------|------------------------------------------|------------------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
|        |                                          |                                          | ($\frac{a}{M} = 0.0$) | ($\frac{a}{M} = 0.5$) | ($\frac{a}{M} = 0.9$) | ($\frac{a}{M} = 0.95$) | ($\frac{a}{M} = 0.998$) | ($\frac{a}{M} = 1.0$) |
|        |                                          |                                          | $\varepsilon = 0.057$ | $\varepsilon = 0.081$ | $\varepsilon = 0.16$ | $\varepsilon = 0.19$ | $\varepsilon = 0.32$ | $\varepsilon = 0.42$ |
| BLRG   | 8.64                                    | -1.59                                   | $10^{19}$ | $9.8 \times 10^{18}$ | $9 \times 10^{18}$ | $10^{18}$ | $10^{18}$ | $8.6 \times 10^{18}$ | $8 \times 10^{18}$ |
| NLRG   | 8.14                                    | -2.92                                   | $1.3 \times 10^{18}$ | $1.2 \times 10^{18}$ | $10^{18}$ | $10^{18}$ | $10^{18}$ | $9 \times 10^{17}$ |
| SSRQ   | 9.29                                    | -0.90                                   | $5 \times 10^{19}$ | $4.6 \times 10^{19}$ | $4.2 \times 10^{19}$ | $4.2 \times 10^{19}$ | $4 \times 10^{19}$ | $3.8 \times 10^{19}$ |
| FSRQ   | 9.01                                    | 0.44                                    | $1.7 \times 10^{20}$ | $1.6 \times 10^{20}$ | $1.4 \times 10^{20}$ | $1.4 \times 10^{20}$ | $1.37 \times 10^{20}$ | $1.3 \times 10^{20}$ |
| Seifert 1 | 7.23                                   | -0.59                                   | $7 \times 10^{18}$ | $6 \times 10^{18}$ | $5.7 \times 10^{18}$ | $5.7 \times 10^{18}$ | $5.4 \times 10^{18}$ | $5 \times 10^{18}$ |

### Table 3: Retrograde motion ($\frac{a}{M} = -0.9$, $\varepsilon = 0.039$).

| Source | $B_H[G]$ | $E_{\text{max}}[\text{eV}]$ |
|--------|-----------|----------------------------|
| BLRG   | $1.7 \times 10^4$ | $1.8 \times 10^{19}$ |
| NLRG   | $6.5 \times 10^3$ | $2.24 \times 10^{18}$ |
| SSRQ   | $1.76 \times 10^4$ | $8.6 \times 10^{19}$ |
| FSRQ   | $1.6 \times 10^5$ | $4.2 \times 10^{20}$ |
| Seifert 1 | $2.7 \times 10^5$ | $1.2 \times 10^{19}$ |
4 The interaction of ultra high energy cosmic rays with intrinsic radiation of active galactic nuclei and quasars

The basic problem for the mechanism considered here is the attenuation of the cosmic ray flux above $\sim 5 \times 10^{19}$ eV in a result of interaction of this flux with the ambient radiation field around of a supermassive black hole. It is well known that, namely, this attenuation by extragalactic background radiation produces the so-called GZK effect. The similar effect by ambient radiation of AGN or QSO should be estimated in our situation.

We estimate of the optical thickness $\tau$ respect to the interaction of the cosmic ray flux with the ambient radiation of AGN and QSO. The value of the optical thickness respect to the $p\gamma$ process is

$$\tau \approx \frac{L\sigma}{4\pi cRk_BT}$$  \hspace{1cm} (7)

where $L$ is the radiation luminosity, $R$ is the characteristic scale distance of the radiation field, $T$ is the temperature of a radiation field, $\sigma$ is the cross-section of the interaction of cosmic protons with the radiation field that is $\sigma \approx 10^{-28}$ cm$^2$ \cite{Atovan & Dermer 2003} (see also Reynoso & Romero (2008)).

The temperature $T$ is determined by the temperature of an accretion disk $T_e$ and it is determined by \cite{Bonning et al. 2007}:

$$T_e = T_0 \left(\frac{M_\odot}{M_{BH}}\right)^{1/4} \left(\frac{L}{L_{Ed}}\right)^{1/4} \left(\frac{R_{in}}{R}\right)^{3/4}$$  \hspace{1cm} (8)

where $R_{in}$ is the radius of an accretion disk.

The relation \cite{Shakura & Sunyaev} corresponds to the standard accretion model of Shakura and Sunyaev. The value of $T_0$ is determined at the radius $R_{in}$ that is closed to the event horizon and corresponds to X-ray temperature, i.e. $T_0 \approx 10^8$ K.

We consider two situations: (a) interaction of the cosmic ray flux with X-ray radiation field and (b) with optical and UV radiation field.

The radiation flux is falling down with a distance as $R^{-2}$. We determine the characteristic scale distance for X-ray radiation field as $R \approx 3R_g$, where $R_g$ is the Schwarzschild radius. For the optical and UV-radiation the characteristic scale-distance is $\sim (10^2 \div 10^3)R_g$. In a result we obtain:

$$\tau \approx 12.8 \left(\frac{L}{L_{Ed}}\right)^{3/4} \left(\frac{M_{BH}}{M_\odot}\right)^{1/4} \frac{1}{\tau^{1/4}}; \ R = rR_g$$  \hspace{1cm} (9)

This Eq.\cite{Bonning et al. 2007} means that $\tau \sim (M_\odot/M_{BH})^{1/2}$, i.e. the increase of the mass of SMBH decreases the optical thickness.

For $M_{BH} = 10^9 M_\odot$ and typical values $L = L_x = 10^{43}$ erg/s and $L_{Opt,UV} \approx 10^{44}$ erg/s we obtain from Eq.\cite{Bonning et al. 2007}:

$\tau = \tau_x \approx 1.2$ and $\tau = \tau_{Opt,UV} \approx 6$. These values demonstrate that the escape of a part of accelerated protons of UHECR from the nearest environment of SMBH is very likely. It should be noted that the cosmic ray luminosity of the active galactic nuclei constitutes a fraction $\sim 10^{-4}$ of the optical one \cite{Dedenko et al. 2008}. This result does not contradict to our estimations.

5 Conclusions

The correlation between the pointing directions of ultra high energy cosmic rays observed by the High Resolution Fly’s Eye experiment and Active Galactic Nuclei visible from its northern hemisphere location can be explained in the framework of acceleration process in AGN as cosmic supercollider. \cite{Kardashev 1993}, \cite{Shatsky & Kardashev 2002, 2006} suggested that this acceleration process produced by a rotating accretion disk around a black hole that is frozen-in magnetic field. This accretion disk is acting as an induction accelerator of cosmic rays.

We estimated the resulting magnetic field in the framework of the magnetic coupling process. The results of our calculation allow to make the conclusion that only the Flat Spectrum Radio Quasars can be revealed as the effective cosmic accelerators. Only for these objects the maximal energy of cosmic rays can essentially exceed the GZK cutoff.

Our conclusions are not totally exclude another probable scenario of UHECR generation. We mean the process of generation of cosmic ray particles with ultra-high energy in a result of acceleration in jets and extended envelopes surrounding AGN. This scenario was recently developed by a number of authors \cite{Dermer et al. 2008, Allard et al. 2008, Berezhko 2008, Bierman et al. 2008}. The decisive choice between various probable scenarios will be done in the result of future cosmic observations and move details confirmation of the Pierre Auger Collaboration data.
Acknowledgments

Our research was supported by the RFBR (project No. 07-02-00535a), Program of Prezidium of RAS "Origin and Evolution of Stars and Galaxies", the Program of the Department of Physical Sciences of RAS "Extended Objects in the Universe".

This research was also supported by the Grant of President of Russian Federation "The Basic Scientific Schools" NS-6110.2008.2.

M.Yu. Piotrovich acknowledges the Council of Grants of President of Russian Federation for Young Scientists, grant No. 4101.2008.2.

We would like to thank academician N.S. Kardashev for very useful comments.

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