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UHECR acceleration in seyfert nuclei

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Abstract. The model of particle acceleration up to energies $E \approx 10^{21}$ eV in Seyfert nuclei is suggested. Particles are accelerated in hot spots of relativistic jets, which damp in dense stellar kernel at distances 1-3 pc from the centre. The energy and chemical composition of accelerated particles depend on the value of magnetic field B in jets. If B~(5-1000) G nuclei with charges Z>1 attain energy $E>10^{20}$ eV, namely: He nuclei (Z=2) get the maximum energy $E \approx 1.5\ 10^{20}$ eV in a magnetic field of B≈40 G; Fe nuclei (Z=26) are accelerated up to $E \approx 9\ 10^{20}$ eV in a field of B≈16 G. In fields of B~1000 G only heavy particles with Z≥23 can be accelerated to $E \geq 10^{20}$ eV. Curvature and synchrotron radiation of accelerated particles is shown to be small. UHECR energy losses in infrared photon fields are negliglible if galactic luminosity is $L<10^{46}$ erg/s.

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1 Introduction

UHECR at energies $E=(4\ 10^{19}\text{-}3\ 10^{20})$ eV were detected at various arrays (Hillas, 1998). Many objects and processes are examined to explain particle acceleration to these energies: cocoons of radiogalaxies (Norman, 1995), annihilation of topological defects (Berezinsky and Vilenkin, 1997), quasars (Farrar and Biermann, 1998), gamma-ray bursts (Totani, 1998), decays of relic supermassive particles (Kuzmin and Rubakov, 1998). We identified directly UHECR sources in (Uryson 1996; 1999; 2001), assuming that UHECR deflection in extragalactic magnetic fields was weak and that possible sources were located within ~100 Mpc around us. The probability analyses showed that possible UHECR sources were moderate Seyfert nuclei with red shifts z<0.01 and lacertidae (BL Lac's).

Acceleration of particles in AGN's to ultra high energies was revealed in (Kardashev,1995): if the vaccum approximation is valid particles could be accelerated to $E\sim Z\ 10^{21}$ eV in electric fields near supermassive black holes. If magnetic lines of force do not curve near black hole poles acceleration up to $E\sim Z\ 10^{27}$ eV is possible. In the model by Kardashev (1995) particles are accelerated in AGN's having distinct jets. Actually, BL Lac's have noticeable jets, but they are not observed in moderate Seyfert nuclei. In this paper we present the model of CR acceleration to $E>10^{20}$ eV in moderate Seyfert nuclei with luminosities $L<10^{46}$ erg/s. We show that accelerated particles can escape sources with small energy losses.

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2 The model of acceleration

Our model is based on AGN's structure revealed in (Vilkoviskij et al., 1999). According to it relativistic jets form in most of Seyfert galaxies, but they merge per ~90% at distances 1-3 pc inside massive stellar kernels. Typical values of jet parameters are: the cross section is $3\ 10^{31}$ cm^2, Lorentz-factor γ is 10. We assume particle acceleration in hot spots of jets. The Mach shock is quasiperpendicular because magnetic field in the jet is parallel to the axis. Actually the shock is colisionless: jets are damping in zones where the temperature is $\sim 10^8$ K, concentration of protons in plasma is $\sim 10^4\text{-}10^5$ cm^{-3}, magnetic fields are ~1 G (Rees, 1987), and so free path for Coulomb scattering is much greater than Debye and Larmor radius of ions. Particles drift along the shock surface until they reach the edge and escape, saturated turbulence providing the scattering. The maximum energy achievable for a particle with the charge Ze due to diffusive shock acceleration in a shock with the velocity $V_j=\beta_j c$ (here c is light velocity) and the size d_j is (Norman, 1995)

$$E_j \approx Ze\beta_j BR_j \text{ erg.} \quad (1)$$

Using jets parameters above, $\beta_j \approx 0.99$, $d_j \approx 6\ 10^{15}$ cm, the maximum energy is

$$E_j \approx 1.9\ 10^{18} ZB \text{ eV.} \quad (2)$$

Parallel to the acceleration in the shock particles loose energy in synchrotron radiation and inverse Compton scattering. Then a maximum energy is determined by the balance of the shock acceleration rate and the synchrotron-Compton losses rate. The value of the maximum energy is given by the expression (Norman, 1995):

$E_s \approx (Mc^2 Ze \beta_j Bct_s)^{1/2}$ erg, (3)

here M is mass of a particle, and t_s is equal to

$t_s = (1.58)^{-1} 10^{15} B^{-2} (A/Z)^3 (m_p/m_e)^2 (m_p c^2)^{-1}$, (4)

where m_p, m_e are proton and electron masses respectively (see also (Ginzburg, 1987)).

Nuclei have $A/Z \approx 2$, and the maximum energy is

$E_{sA} \approx 6.6\ 10^{20} (Z/B)^{1/2}$ eV. (5)

Protons gain the maximum energy of

$E_{sp} \approx 1.65\ 10^{20} B^{-1/2}$ eV. (6)

With the condition $E_j = E_s$ one finds the magnetic field strength B_{CR} in which particles of different numbers Z gain maximum energy:

$B_{CR} = (3.5\ 10^2)^{2/3} Z^{-1/3}$. (7)

(In fields $B < B_{CR}$ the maximum energy is $E = E_j$, in fields $B > B_{CR}$ the maximum energy is $E = E_s$.) From (2) and (5-7) it follows that protons gain the maximum energy of $E_{max\ p} \approx 3.7 \cdot 10^{19}$ eV in a magnetic field of $B_p \approx 19.6$ G, He nuclei (Z=2) gain the energy of $E_{maxHe} \approx 1.5\ 10^{20}$ eV in a field of $B_{He} \approx 39.5$ G, and Fe nuclei (Z=26) attain $E_{max\ Fe} \approx 9\ 10^{20}$ eV in a field of $B_{Fe} \approx 16$ G. At present the value of magnetic field frozen in the jet is unknown. In the fields of B~(5-40) G nuclei with $Z \geq 10$ are accelerated up to $E \geq 2\ 10^{20}$ eV, lighter nuclei gain the energy $E \leq 10^{20}$ eV. In a field of B~100 G nuclei with Z>2 are accelerated to $E \geq 10^{20}$ eV. If a field is B~1000 G only particles with $Z \geq 23$ are accelerated to $E \geq 10^{20}$ eV. Protons attain the energy of $E < 4\ 10^{19}$ eV in any fields.

3 Escape from Sources

Accelerated particles do not scatter in the bow shock preceding the hot spot, as the bow shock advances more slowly than the jet itself (it is because the density of the jet is smaller than the density of the external gas) (Chakrabarti, 1988). Particles loose a part of energy in photopion reactoins with infrared photons and in synchrotron and curvature radiation.

Photopion losses could occur in the broad line region (BLR), surrounded by an optically and geometrically thick torus of dusty molecular material (Pier and Krolik, 1993). Radiation fields of the BLR and of the torus are reradiated by clouds which constitute BLR. However losses in the BLR are negligible if the source luminosity is $L < 10^{46}$ erg/s (Norman, 1995). These are luminosities of moderate Seyfert galaxies which we identified as UHECR sources. Accelerated particles do not get into the torus if the angle i between the line of sight and the normal to the disk is small, assuming the torus is coplanar with the galactic disk. This angle depends on the axial ratio: cos(i)=b/a (Simcoe et al., 1997), therefore galaxies-sources have a relatively large axial ratio.

In the hot gas flow synchrotron losses are negligible because the magnetic field in it is oriented mainly toward the flow.

Curvature losses of the particle is equal to

$-dE/dt = 2/3 (Ze)^2 c (E/Mc^2)^4 \rho^{-2}$, (8)

where ρ is the radius of curvature of a magnetic line of force (Kardashev,1995). From here the energy decreases twice during the time

$T_{curv} = 7/2 (Mc^2)^8 E^{-3} (Ze)^{-2} \rho c^{-1}$. (9)

A particle of an energy E propagates along a magnetic line of force at the distance R_{line} on time

$t \approx R_{line}/c = 4.6\ 10^9$ s. (10)

If $t < T_{curv}$ (11)

a particle looses less than a half of it energy E on this distance. One finds the condition for (10) as follows. A particle escapes the galaxy coming up the regions where it Larmor radius is $r_L \geq 5$ kpc (Pochepkin et al, 1995). (Here we assume that typical dimensions of spirals are similar to those of our galaxy. The most part of Seyfert galaxies are spirals.) Ultrarelativistic particles have $r_L \approx E/(300ZB)$, where energy E is measured in eV, the magnetic field strength B is measured in G, and r_L is measured in cm. The condition $r_L \geq 5$ kpc is valid if $B \leq 10^{-5}$ G. Assuming $B \sim R^{-3}$, and B~1 G at R~1kpc [10] one gets $R_{line} \approx 46$ pc. The radius of curvature of a line of force of the dipole magnetic field is $\rho = 4R^2/(3a)$, R, a being distances to the dipole centre and its axis (Kardashev,1995). From here and from (9-11) one finds that particles at $E = E_{max}$ travel the distance $R_{line} \approx 46$ pc with small curvature losses if they depart from the jet axis at distances: $a_p \approx 0.01$ pc for protons, $a_{He} \approx 0.03$ pc for He nuclei, and $a_{Fe} \approx 0.04$ pc for Fe nuclei.

What part of accelerated particles looses less than a half of energy in curvature radiation?

These particles have deviation angles from the jet axis of

$\theta \leq a/R_{line} = 6.5\ 10^{-4}$. (12)

In the shock system particles scatter isotropically. Therfore one finds the fraction of particles with small curvature losses as follows. The deviation angle θ is expressed by the deviation angle θ^* in the shock system (Landau and Lifshits, 1993):

$tg\theta = 1/\gamma(\beta_j + \cos\theta^*)^{-1} \sin\theta^* \approx 0.14 \sin\theta^* (1+\cos\theta^*)$. (13)

For $\theta < 0.02$ one has $\cos\theta^* \approx 1$, $\sin\theta^* \approx \theta^*$, and $\theta \approx 0.07\theta^*$. From here $\theta^* \approx 0.01$, and the fraction of particles with deviation angles (12) is equal to $0.01/\pi \approx 3\ 10^{-3}$. Thus 1 particle among 300 accelerated ones escapes the source without curvature losses.

4 Conclusion

We supposed the model of UHECR acceleration in Seyfert nuclei. The unknown parameter of the model is magnetic field strength in jets. The maximum energy achievable depends on a field strength and is proportional to a particle charge Ze. In fields of B~(5-40) G nuclei with $Z \geq 10$ are accelerated to $E \geq 2\ 10^{20}$ eV, lighter nuclei attain energies of $E \leq 10^{20}$ eV. Fe nuclei attain the most high energy of $9\ 10^{20}$

eV in a field of B≈16 G. In fields of B~1000 G only heavy particles with Z≥23 can be accelerated to $E \geq 10^{20}$ eV. Protons gain energies of $E<4\ 10^{19}$ eV in fields of any strength from ~5 to 1000 G. All particles escape sources without photopion losses if galactic luminocity is $L<10^{46}$ erg/s (Norman, 1995), and in addition galaxies sources have a relatively large axial ratio. Synchrotron losses are negligible. One particle among 300 accelerated ones do not loose energy in curvature radiation.

Chemical composition of UHECR make our model distinguishable from top- down models (Kuzmin and Rubakov, 1998), namely lack of protons and presence of nuclei with Z>2. If the model is true it is possible to summarize fields in jets using spectra and chemical composition of UHECR. They will be measured at AGASA, at Pierre Augier, and at EAS-1000 (Cronin, 1992; Fomin et al., 1999).

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