Acceleration of Ultrahigh Energy Cosmic Rays by Shocks in Active Galactic Nuclei

Yasuko S. Honda,[1] and Mitsuru Honda[2]
(1) Department of Electrical and Information Engineering, Kinki University Technical College, Mie 519-4395, Japan
(2) Plasma Astrophysics Laboratory, Institute for Global Science, Mie 519-5203, Japan

Abstract

We introduce our model for collimation and magnetic field generation of electron-positron-ion jets in active galactic nuclei (AGN). The stream along the jet direction with the excess electrons generates the toroidal magnetic field, which contributes to self-pinching of the constituent current. The huge net current necessarily split into many filaments, each carrying one unit current characterized by the Alfvén limit. The resultant filamentary structures and transverse magnetic field well account for recent observations. Moreover, if a shock wave is established and passing through along the jet axis, cosmic rays can be effectively accelerated by the first order Fermi mechanism. Considering some energy loss processes, we estimate the attainable maximum energies of accelerated particles up to 10^{21} eV, which are in good accordance with recent data.

1. Introduction

High resolution up-to-date observations provide some detailed structures of astrophysical jets. Especially, AGN jets extend up to mega-parsec scales with narrow opening angles in some objects (e.g. NGC 6251: [1,2]; M87, PKS 0637-752: [3]). It is revealed that the direction of magnetic field vectors is likely to be transverse to the jet axis (e.g. 1803+784: [4]) by rotation measures using very long baseline interferometry (VLBI). There also exists an observation of a double-helical structure inside the extragalactic jet (3C 273: [5]).

In this paper, we present that the toroidal magnetic field induced by electron-positron flow is a favored candidate for the collimation force of the AGN jets. Our model leads to the observed filamentary structures (Galactic center: [6]) and transverse magnetic field as natural consequences. Furthermore, if a shock wave is formed and propagating through the jet, it will be an effective accelerator of ultrahigh energy cosmic rays. We calculate the maximum energies of accelerated particles, considering three spectral types of turbulent magnetic fields.

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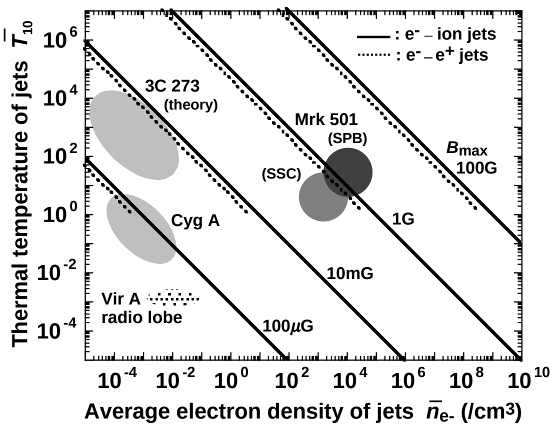

Fig. 1. Maximum possible magnetic fields $B^s_{\theta,\max}$ for a given average electron density $\bar{n}_{e-}$ and temperature ($\bar{T}_{10} \equiv \bar{T}/10^{10}$ K) of jets [7]. Note that all the quantities are in the ion rest (jet) frame. The solid and dotted lines show the maximum fields for the electron-ion jets ($f_p = 0$), and the electron-positron jets ($f_p = 1$), respectively. The shaded areas indicate the allowable parameter regions of some well-known AGN jets: Cyg A [2], Virgo A [10], 3C 273 [11], and Mrk 501 [12,13].

2. Parsec-Scale Stable Jets with Transverse Magnetic Fields

We at first introduce our model for collimation and magnetic field generation of electron-positron-ion jets [7]. In a fully relativistic regime of $T > 10^{10}$ K, the jet could consist of electrons, positrons, and a small portions of ions, i.e., $n_{e-} \sim n_{e+} \gg n_i$, where n_{e-}, n_{e+}, and n_i are the number densities of electrons, positrons, and ions, respectively. Around central engines, fast electron-positron flows relative to ion motions can be easily organized owing to the difference of their inertia. The current due to the excess electrons $n^*_{e-} = n_{e-} - n_{e+} = \langle Z^* \rangle n_i$ induces the toroidal "self"-magnetic field B^s_θ, which participates in self-pinching the electron-positron gas and in assembling the ions radially inward on the hydrodynamical timescale [8,9]. Employing the charge neutral condition, and diffuse density profile for self-consistent beam-plasma equilibrium, we obtain the maximum value of magnetic field near the filament surface:

$$B^s_{\theta,\max} \simeq 0.33(1+f_p)^{1/2} \left(\frac{\bar{n}_{e-}}{10^4 \mathrm{cm}^{-3}}\right)^{1/2} \left(\frac{\bar{T}}{10^{10}\mathrm{K}}\right)^{1/2} \ \mathrm{G}, \tag{1}$$

where f_p denotes the ratio of positron/electron densities, $0 \le f_p \equiv n_{e+}/n_{e-} < 1$.

In Fig.1, for the perfect charge neutral situation, we present the allowable range of magnetic fields for a given density and temperature of jets. The maximum given by equation (1) may be a theoretical limit of the field strength of the astrophysical jets. For Mrk 501 the field strength predicted by the synchrotron self-Compton (SSC) model, which can explain a double-humped spectrum [12], is close to the theoretical limit. On the other hand, the spectral fitting by the modified synchrotron proton blazar (SPB) model [13] requires a somewhat stronger field for the same object, as shown in Fig.1. We also mention that in contrast to the MHD model, the self-consistent Vlasov-Maxwell analysis indicates that the diffuse density profile bounds the growth rate of the resistive hose instability. The resultant lifetime of the jet can be fairly estimated to be $\tau_j > 10^4$ yr [7], which implies the jet as an particle accelerator is stable during a sufficiently long time.

3. Cosmic Ray Acceleration by a Quasi-Perpendicular Shock in Jets

A Shock wave which are penetrated by the strong toroidal magnetic field in an AGN jet sets up an ideal accelerator for energetic cosmic rays. According to the first order Fermi mechanism, particles (mainly protons) are repeatedly accelerated by the shock up to ultrahigh energies. The maximum energy is, however, considered to be restricted by the following three processes: collisions with ambient photons, synchrotron radiation, and adiabatic losses. In the region distant from the central engine, p-γ collision is ineffective because the energy density of photons is significantly lower than that of magnetic field. The acceleration timescale $t_{\rm acc}$ is then determined by the competition of the other two processes:

$$t_{\rm acc}(\theta_1, B_1, \gamma_p) = \min[t_{\rm ad}, t_{\rm syn}(B_1, \gamma_p)], \tag{2}$$

where θ_1 and B_1 are the inclination and strength of the magnetic field measured in upstream rest frame, respectively, and γ_p is the Lorentz factor of accelerated protons. The synchrotron loss timescale $t_{\rm syn}$ is introduced in ref.[14]. The timescale of adiabatic losses can be expressed as $t_{\rm ad} \sim L/\Gamma c$, where Γ and L are the Lorentz factor and length of jets (for Mrk 501: $L \sim 10^{18}$ cm [15]) and c is the light speed. The shock can exist stably for the acceleration time because $L \ll c\tau_j$. The maximum energy is described by $E_{\rm max} = \gamma_p m_p c^2$, where m_p is the proton rest mass.

In Fig.2, we plot the attainable maximum energies of accelerated protons $E_{\rm max}$ against the field strength B_1. Three spectral types of turbulent magnetic fields are considered: Bohm's diffusion limit which is often used for simplicity, Kolmogorov, and Kraichnan (for strong magnetic field) [16] turbulence. It is shown that adiabatic losses are effective in weak field situation, otherwise synchrotron losses contribute dominantly. In all three cases the peak of maximum energies exhibits around $B_1 \simeq 10^{-1}$ G, which is consistent with the limit derived from SSC model [12]. The highest energy peak is above 10^{21} eV for Kolmogorov turbulence, which is common for astrophysical environments. The peak of the maximum energy at $\theta_1 = 60^\circ$ is about 6 times larger than that of a parallel shock ($\theta_1 = 0^\circ$). The inclination is restricted to $\leq 60^\circ$ by the de Hoffmann-Teller limitation.

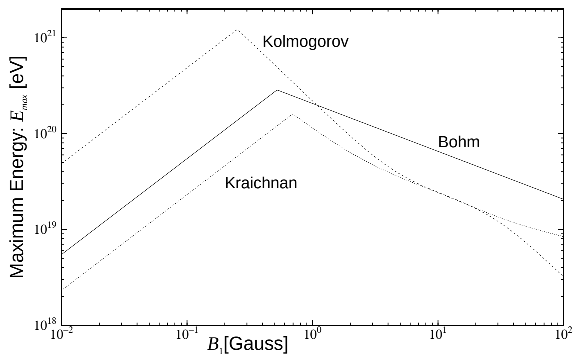

Fig. 2. Maximum energies of accelerated protons as a function of upstream magnetic field B_1. All physical parameters are chosen for Mrk 501 [15]. The field inclination is fixed at $\theta_1 = 60°$. Three spectral types of turbulence are indicated by labels.

4. Conclusions

The current with excess electrons contributes to the jet collimation and generation of toroidal magnetic fields. The strength and inclination of the magnetic fields are quite favorable for cosmic ray acceleration in AGN jets. The attainable highest energy of accelerated protons realized in the Kolmogorov turbulence is above 10^{21} eV, which is consistent with the latest AGASA data [17].

References

1. Bridle A. H., Perley R. A. 1984, ARA&A 22, 319
2. Carilli C. L., *et al.* 1998, Phys. Plasmas 5, 1981
3. Hirabayashi H. 2001, Butsuri 56, 308 (in Japanese)
4. Gabuzda D. C. 1999, NewA Rev. 43, 691
5. Lobanov A. P., Zensus J. A. 2001, Science 294, 128
6. Yusef-Zadeh F., Morris M., Chance O. 1984, Nature 310, 557
7. Honda M., Honda Y. S. 2002, ApJ 569, L39
8. Honda M., Meyer-ter-Vehn J., Pukhov A. 2000, Phys. Rev. Lett. 85, 2128
9. Honda M., Meyer-ter-Vehn J., Pukhov A. 2000, Phys. Plasmas 7, 1302
10. Owen F. N., Eilek J. A., Kassim N. E. 2000, ApJ 543, 611
11. Aharonian F. A. 2001, preprint (astro-ph/0106037)
12. Kataoka J. *et al.* 1999, ApJ 514, 138
13. Mücke A., Protheroe R. J. 2001, Astropart. Phys. 15, 21
14. Biermann P. L., Strittmatter P. A. 1987, ApJ. 322, 643
15. Giovannini G. *et al.* 2000, Adv. Space Res. 26, 693
16. Kraichnan R. H. 1965, Phys. Fluids 3, 1385
17. Takeda M. *et al.* 1998, Phys. Rev. Lett. 81, 1163