Nonlinear Dynamics and Applications. Vol. 13 (2006) 192 - 199

Long-term evolution of jets in halos of active galaxies

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We analyze long-term evolution of jets from their origin in accretion disks of active galactic nuclei to their destruction in far-halos of galaxies. Based on the analytical solutions of relativistic magnetohydrodynamics equations we show that interactions of charged jet with intergalactic medium are not effective in jet destruction. High stability of jet in the nearest halo region are explained and proved. We show that the only mechanism of jet particles changing their trajectories is their interaction with cold dark matter particles in far regions of galactic halo. Numerical simulations result in the most probable candidate for such cold dark matter particles — primordial micro black holes.

PACS numbers: 98.54.Cm, 98.62.Nx, 04.70.-s, 95.35.+d, 95.75.-z
Keywords: galaxies: active, galaxies: jets, black hole physics

1. Introduction

Jets are observed in various astronomical objects, such as active galactic nuclei (AGNs), X-ray binaries (XBs), and young stellar objects (YSOs). These astrophysical jets have variety in the linear size. In AGNs, jets extend more than several hundreds kpc and are several times larger than the host galaxies. In XBs and YSOs, the jets are much smaller than those in AGNs. The size of the jets ranges from 0.1 pc to 100 pc. Astrophysical jets show variety also in the velocity and luminosity. Despite all these varieties in the scale, astrophysical jets have common features. (1) Velocities of jets are of the order of the escape velocity of the source. (2) Jets are collimated well and essentially cylindrical. (3) Jets involve complex internal structure, such as wiggling and knots. (4) Jets show often S-shaped point symmetry around the source. (5) Jets vary their shapes and directions on short time scales. (6) Jets associate disks of which planes are perpendicular to the jet axis. These similarities suggest that astrophysical jets have common physical mechanisms in the formation and collimation. Many researchers have studied various aspects of astrophysical jets both observationally and theoretically to shed light on the mechanisms of formation and collimation. In observations, jet sources have been studied in wide range of wavelength, from radio to X-ray. In radio region, hundreds of jets have been found in AGNs. Their velocities or morphologies are studied statistically. In infrared and optical region, internal structure of jets from YSOs is studied. In X-ray region, using spectra and their variabilities, the structure and dynamics of the most inner region of jet sources, at which the jets accelerate, are investigated. Recently, data of higher spatial or energy resolution are available with interferometer techniques and space observatories. For examples, in radio, with very long baseline interferometer (VLBI) techniques images of radio jets with resolution of milli-arcsecond are obtained. In infrared and optical, the NASA's Hubble

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space telescope has taken images of 0.1 arcsecond resolution, which are not available with ground-based telescopes. In X-ray, the ASCA satellite observes several KeV images with 0.2 KeV energy. Moreover, multiwavelength observations are carried out owing to cooperation of observatories with different target wavelength. In multiwavelength observations, targets are observed in different wavelengths simultaneously. The multiwavelength observations of the X-ray binary GRS1915+105, known as a transient X-ray source, reveal that there is the time correlation between X-ray flares and superluminal radio jet ejections. In theories, formation and collimation of jets are investigated in various fields: structure of accretion disks, acceleration and collimation processes of jets with numerical simulations, shock waves in accretions disk, particle acceleration mechanisms at shocks, etc. There are two main branches of accretion disk models: Standard accretion disk model and advection dominated accretion flow (ADAF) model, The standard accretion disk models were initiated by Shakura & Sunyaev (1973) [1]. Although the standard models explain many aspects of observational features of accretion disks, there are still some features that can not be accounted for, e.g., spectra of low luminosity AGNs. Other accretion solutions, ADAF models, are the spectra of low luminosity AGNs. Various kinds of jet acceleration mechanisms have been proposed. Jets are accelerated by gas pressure, magnetocentrifugal force, magnetic pressure, or radiation pressure. There are some collimation processes proposed: collimation by funnel flow, pinch effect of plasma, or cylindrical environment.

2. Observational features of astrophysical jets

2.1. Velocity

The velocities of astrophysical jets are known to be of the order of the escape velocities of the central objects. In AGNs and XBs, the velocities of jets range from mildly relativistic ($v \sim 0.2c$) to ultra-relativistic ($v \sim 0.995c$ or the Lorentz factor $\Gamma \sim 10$) [2].

In AGNs, relativistic jets are suggested by the fact that one-sided radio jets are commonly observed [3]. Since these one-sided jet sources associate double radio lobes, and since the lobes are supplied with their energy by the jets, the jets are intrinsically bipolar. The apparent asymmetry of the jets comes from a relativistic beaming effect, i.e., we observe a strong approaching jet as a one-sided jet and hardly observe a week receding jet. Another observational evidence of the relativistic jets is a super luminal motion. For examples, in 3C120 [4] and the quasar 1928+738 [5], proper motion of knots in the radio jets exceeds the speed of light apparently. This super luminal motion is interpreted as a relativistic effect caused by radio jets with bulk velocity close to the speed of light pointing toward the observer. Also in the X-ray binaries, GRS 1915+105 and GRO 1655-40 [6], super luminal motion is observed. The intrinsic velocities of the jets are estimated to be about $0.9c$. In YSOs, the velocities of jets are of the order of 100 km s^{-1}, which are close to the escape velocities of the protostars with the mass of $\sim 1M_{\odot}$ [7].

2.2. Collimation

Collimation of astrophysical jets is known very well. The collimation factor, which is defined as the ratio of the length to the diameter of jets, is several hundred for AGNs and 3-30 for XBs and YSOs. Radio jets from AGNs are extremely well collimated. The radio jets extend more than several tens kpc. Radio jets from the powerful AGNs are typically straighter and better collimated than those associated with weaker AGNs [8].

2.3. Internal structure

Astrophysical jets often take straight filled morphology. If we observe the jets with higher spatial resolution, we find their internal structures: knots and wiggling.

Knots are often observed in astrophysical jets. Wiggling is observed in some jet sources. The wiggling is seen not only in the radio intensity morphology but also in the directions of the magnetic field in the jets. These internal structures in astrophysical jets are thought to originate from episodic ejection or the precessing ejection of jets from the central object, as described in the following subsection 'S-shaped symmetry.'

2.4. S-shaped symmetry

Astrophysical jets generally show S-shaped point symmetry with respect to the source [9]. The jets, including the knots and kinks, are highly shaped point symmetric for the length of 30 kpc. Although most AGN jets show point symmetry, some AGNs jets have mirror symmetry (e.g., 3C449). The mirror symmetry is thought to be due to sweeping back of point symmetric jets by the proper motion of the galaxy through the surrounding intergalactic medium, since mirror symmetric jets are found almost exclusively in clusters of galaxies. In fact 3C449 is a member of the open cluster of galaxies Zw2231.2+3732. In the mirror symmetric jets, knots are also distributed mirror symmetrically.

Point symmetry is also seen in jets from XBs. The jets from SS433 show clear S-shaped point symmetry of knots, with the jet axis precessing. Point symmetric distribution of knots is also seen in HH jets. The degree of the symmetry is higher in the inner region.

These S-shaped point symmetries of jet morphology and knots distribution suggest that the morphology and internal structure of jets originate from activities (e.g., precession and episodic ejection of jets) of the central source (internal origin), not from inhomogeneous distribution of the environmental gas (external origin).

2.5. Variability

In AGNs and XBs, the activity of central object has been observed in various wavelength, and the data have given information on the physical environment of jet forming region. We here describe the multiwavelength observations of flares from the AGN, Markarian 421, and the XBs, GRS 1915+105 and GRO 165540. Mrk421 is the closest BL Lac object at $z = 0.0308$ [10]. Mrk421 is one of the most luminous AGNs in the sky, and therefore has been observed frequently with wide wavelength that ranges from radio, optical, X-ray, to TeV -ray. Takahashi et al. (1996) [11] observed an X-ray flare from Mrk421 on 1994 May 16 with the X-ray satellite ASCA. They found that the flux peak in the hard X-ray band (7.5 keV) leads that in the soft X-ray band (2 keV) by ~ 1 hr. The TeV flare that associated with the X-ray flare was simultaneously observed by Kerrick et al. (1995) [12] with EGRET γ-ray detector (> 100 MeV). The TeV flare peak preceded the X-ray peak by 27 hr. This "soft lag" may be due to synchrotron life time effects [11]. Similar "soft lag" was observed other BL Lac objects, PKS2155-304 [13] and H0323+022 [14]. Also in the XBs, GRS 1915+105 and GRO 1655-40, multiwavelength observations have been done. These "micro quasars" are useful to study time-dependent phenomena, since they evolve dynamically faster than AGNs. The dynamical time scale of "micro quasars" is of the order of milli second, and is about 10^{5-7} times faster than that in AGNs, since the mass of the compact sources in "micro quasars" is a few solar mass and is much less than that in AGNs. In GRS 1915+105 the correlations between hard X-ray flux and radio flux were detected in several significant radio flares that occurred in the period from 1994 September to 1996 March [15]. In the flares the bursts in radio emission tend to be late by several days to the bursts in X-ray emission. These time variations suggest that the jet formation is closely related to activities of an accretion disk.

2.6. Theories and problems

As noted in the previous subsections, observations have revealed various aspects of astrophysical jets: (1) jets are very fast (relativistic jets are common in AGNs and XBs) and are highly collimated (the ratio of length to width ranges from 10 to 100); (2) jets often associates accretion disks perpendicular to the jet axis (e.g., NGC4261, M87, and HH31); (3) jets ejections have close relation to activities of accretion disks, (in some XBs radio jets emanate after X-ray flares episodically). To account for these observations, many theorists have investigated accretion disks and jets therefrom. Accretion disk models have widely succeeded in accounting for many observational aspects of AGNs, CVs, and YSOs, e.g., the UV bump in AGN spectra, high and low states of CVs. Although accretion disk models succeed in understanding the spectra, they are not effective tools to understand the formation and collimation mechanisms of jets. Jet formation and collimation mechanisms have been intensively investigated with numerical simulations. Mainly by solving hydrodynamical equations numerically, many researchers propose various kinds of jet acceleration and jet collimation mechanisms [16].

There are three main problem linked with jets today: (1) what are jets made of, (2) why jets are highly collimated and relativistic, and (3) what is the reason of jet shape changes. In this paper we try to answer the last two questions. We study jet stability properties by means of analytical solving of MHD equations. We analyze several mechanisms of jet deforming factors. We found the single mechanism which is able to explain jet deformation. It is connected with scattering of jet electrons by massive cold dark matter (CDM) particles. We perform some numerical simulations to prove this hypothesis.

3. Initial stage of jet trajectory

Lets consider the process of jet slowing down via its mass increase by means of charged particle capture in the interstellar and intergalactic medium by jet magnetic field. Applying impulse conservation law:

$$\dot{M}_J t \frac{v_0}{\Gamma_0} = \frac{v}{\Gamma}(\dot{M}_J t + rS\rho), \tag{1}$$

where $\dot{M}_J$ — rate of jet matter transfer, v_0, Γ_0 — its initial velocity and Lorentz factor, S — effective cross section of particle capture by magnetic field, ρ — density of surrounding medium. From the last formula we have expression for jet moving away velocity

$$\vec{v}_J(z,t) = -\frac{\Gamma_0}{\langle\Gamma\rangle_t}\frac{\dot{M}_J v_0}{\dot{M}_J t + rS\rho}\hat{e}_z, \tag{2}$$

where $\langle\Gamma\rangle_t$ — time-averaged value of Γ. In the initial state jet consists of a beam of high-energy particles (protons/positrons or electrons) of radius $r \sim R_h = GM/c^2$. Then when interacted with surround medium it could be deformed. For mathematical description lets consider invariant MHD system of equations:

$$\begin{cases} \frac{\partial B_\varphi}{\partial t} = 0; \\ \frac{\partial B_r}{\partial t} = -\frac{\partial}{\partial z}\left(v_z B_r\right); \\ \frac{\partial B_z}{\partial t} = -v_z \frac{\partial B_r}{\partial r}. \end{cases} \tag{3}$$

In it $\vec{B} = (B_r,\ B_\varphi,\ B_z)$ are magnetic field of jet current. From the first equation of (3) it follows:

$$B_\varphi = \mathrm{const} = B_{\varphi 0}. \tag{4}$$

If $B_r = B_r(r,t)$, then

$$\begin{aligned}
&\tfrac{\partial B_r}{\partial t} = -B_r \tfrac{\partial v_z}{\partial z} \Rightarrow \left[\tfrac{dB_r}{B_r} = -\tfrac{\partial v_z}{\partial z} dt, \quad \tfrac{\partial v_z}{\partial z} = \tfrac{\Gamma_0}{\langle\Gamma\rangle_t} \dot{M}_J v_0 t \tfrac{S\rho}{(\dot{M}_J t + zS\rho)^2}\right] \Rightarrow \\
&\Rightarrow \ln|B_r| = -\tfrac{\Gamma_0}{\langle\Gamma\rangle_t} v_0 S\rho \int \tfrac{\dot{M}_J}{t} dt (\dot{M}_J t + zS\rho)^2 = \\
&= -\tfrac{\Gamma_0}{\langle\Gamma\rangle_t} \tfrac{v_0 S\rho}{\dot{M}_J} \left[\tfrac{S\rho z}{\dot{M}_J t + Sz\rho} + \ln(\dot{M}_J t + S\rho z)\right],
\end{aligned} \tag{5}$$

and finally we have:

$$B_r = C(r) \exp\left\{-\frac{\Gamma_0}{\langle\Gamma\rangle_t} \frac{v_0 S\rho}{\dot{M}_J} \left[\frac{S\rho z}{\dot{M}_J t + Sz\rho} + \ln(\dot{M}_J t + S\rho z)\right]\right\}, \tag{6}$$

where $C(r)$ — arbitrary function of coordinate r. When $B_r \neq B_r(z)$, then

$$\begin{aligned}
\tfrac{\partial B_r(r,t)}{\partial t} = -\tfrac{\partial v_z}{\partial z} B_r \Rightarrow \tfrac{dB_r}{B_r} = -\tfrac{\partial v_z}{\partial z} dt \Rightarrow \ln|B_r| = -\tfrac{\partial v_z}{\partial z} t + C_1(r) \Rightarrow \\
\Rightarrow B_r = B_{r0} \exp\left\{-\tfrac{\partial v_z}{\partial z} t\right\}.
\end{aligned} \tag{7}$$

From the derived expressions $\partial B_z / \partial t = 0$, and

$$B_z = B_{z0}. \tag{8}$$

Obviously, $B_{z0} = 0$, therefore $B_z = 0$. Component B_φ of magnetic induction vector is equal to magnetic field of straightforward jet current J:

$$B_\varphi = \frac{2J}{cr} = \frac{2}{cr} \frac{e}{m_0} \dot{M}_J. \tag{9}$$

Jet deformation could take place as a result of restructure of its magnetic field via its interaction with interstellar and intergalactic medium plasma. Sufficient condition of field restructure is:

$$m_0 n c^2 \left(\frac{1}{\sqrt{1 - v^2/c^2}} - 1\right) \geq \frac{B_\varphi^2}{4\pi}, \tag{10}$$

We have from there condition of medium concentration, sufficient for jet structure change

$$n \geq \sqrt{1 - v^2/c^2} \frac{e^2}{\pi c^4 m_0^3} \dot{M}_J^2 \frac{1}{r^2}. \tag{11}$$

To solve this inequality it is necessary to derive expression for jet velocity. With effective capture cross section $S = \pi R_{eq}^2$ we have

$$\frac{B_\varphi^2}{4\pi} = \frac{1}{\pi c^2 r^2} \frac{e^2}{m_0^2} \dot{M}_J^2 = n m_0 \Gamma, \tag{12}$$

equation for velocity $v_z \equiv dz/dt$ is:

$$v_0 \Gamma_0 t = \frac{dz}{dt} \left[1 - \left(\frac{dz}{dt}\right)^2 \frac{1}{c^2}\right]^{-1/2} + z \frac{dz}{dt} \frac{e^2}{c^2 m_0^2} \dot{M}_J. \tag{13}$$

Analyzing differential equation (13), its obvious, that slowing down process of jet is not effective. It is connected to large value of Γ up to $\simeq 10^5$ and very low density of surrounding medium.

4. Numerical simulations of jet destruction

In the previous section our solutions of MHD equations prove high stability of initial stages of jet propagation. But the observations show strong deformations of jet trajectories in the outer regions of parent galactic halos. As it was shown in previous section, MHD interactions of jet particles with intergalactic medium aren't able to curve jet trajectory. Other mechanism was analyzed in [17]. According to it jets could be curved because of energy loss via Compton and synchrotron mechanisms. This mechanism isn't also effective enough to curve jet. We propose another hypothesis:

- jets are deformed due to the process of frequent inelastic scattering by invisible halo particles.

The only candidate for such a kind of particles could be primordial micro black holes.

Lets consider two dimensional scattering model. Its main parameters are: effective cross section of scattering particles a_s, concentration of scattering particles n_s, scattering $s(\theta)$, and fraction of electron energy after scattering κ. We define another parameter — mean free path l:

$$l = \frac{1}{2\pi a_s^2 n_s}, \quad (a_s \ll 1\ \text{cm}^2). \tag{14}$$

Numerical simulations was performed in Mathematica 5.0 system using Monte Carlo method. At $t = 0$ jet electron is in zero point of Cartesian plane XY (Y coordinate is directed toward initial jet particle motion) and have its first inelastic collision. Electron moves aside from its initial trajectory on the random angle $\phi = s\,(\text{random}[0, 2\pi])$, which is distributed as $s(\theta)$ ($\text{random}[0, 2\pi]$ — uniformly distributed at $[0, 2\pi)$ random value, generated with Mathematica 5.0 random number generator). Electron energy after the first collision is $\Gamma_1 = \kappa\Gamma_0$. There are scheme of numerical algorithm below:

$$\left[\begin{array}{rcl} x_0 &=& y_0 = 0, \\ \phi_0 &=& \frac{\pi}{2}, \\ \phi_k &=& s\,(\text{random}[0, 2\pi]), \\ x_k &=& x_{k-1} + l\sin(\phi_k + \phi_{k-1}), \\ y_k &=& y_{k-1} - l\cos(\phi_k + \phi_{k-1}), \\ \Gamma_k &=& \kappa^k \Gamma_0, \\ t_k &=& t_0 + \sum\limits_{j=1}^{k} \frac{l\Gamma_k}{c\sqrt{\Gamma_k - 1}}, \\ && k = 1, 2, 3, \ldots \end{array}\right. \tag{15}$$

For correlation of parameters of the model with experimental data we use data from image catalogue of radio galaxies and quasars [18]. Therefore the main input model parameters are shape of deformed jet part and its linear size. In our model the mean lengthwise size of deformed jet part $\langle D \rangle = 300$ kpc. Other parameters are mean free path of an electron l and number of collisions N. Simulations were performed for one particle with scattering indicatrix of two kinds. When $s(\theta) = s_1(\theta)$,

$$s_1(\theta) = \begin{cases} \theta, & \theta \le \pi \\ 0, & \theta > \pi \end{cases}, \tag{16}$$

region of scattering becomes close to circle with number of collisions N increase. That doesn't fit the experimental data. The second indicatrix $s_2(\theta)$ is chosen according the nature of the process of ultrarelativistic particle deceleration. At high energies of electron it bends at small angles. When it decelerated enough its angular distribution should be close to uniform. There is an example of function with such a constraint is satisfied:

$$s_2(\theta, i) = (-1)^i \frac{\zeta\theta}{N - i + 1} + \frac{\pi}{2}, \tag{17}$$

where i — number of collision, ζ — arbitrary constant. The best fit of the experimental jet shape is satisfied with $\zeta = 0,03N$. According to this model we determine number of collisions before the total slowing down. It is equal to 1130 for $\kappa = 0,95$. The results of our numerical simulations are presented in fig. 1. This plot corresponds to the maximal number of scatters used in simulations — 11 000. When further increased, N leads to very long duration of computer calculations.

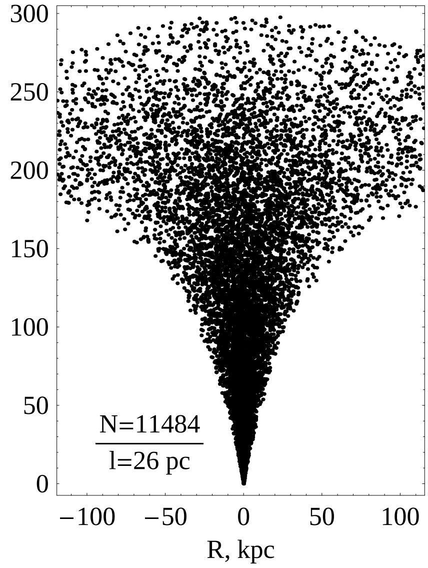

FIG. 1. Deformation of jet in far-halo regions of parent galaxies in consequence of scattering by invisible massive halo particles ($\zeta = 0,03\ N$).

5. Discussion and conclusion

In section 3 we found, based on relativistic magnetohydrodynamics equations, that initial jet trajectory is stable and collimated, jet particles don't lose their energy Γ due to interactions with intergalactic medium. In section 4 we propose numerical algorithms and codes for numerical Monte Carlo simulations of scattering of jet electrons by far-halo cold darc matter particles. We simulate final jet evolution stages, their inelastic slowing down and spatial deformation. Simulations are performed with variations of parameters: number of scatters (up to 11000), and mean free path (≥ 25 pc). Its a pity that these results doesn't allow to estimate cold dark matter particle density. That is due to large uncertainties of used parameters and the indicatrix s_2.

According to our simulations we present hypothesis of jet deformation and decelerating in consequence of its particle inelastic scattering by invisible halo particles. Lets consider probable candidates for such a kind of particles. Their properties should be rather unique: comparatively small size ($\sim 1\ \mu$m), absence of any emission, possibility of transformation of large energy. The first probable candidate for such hypothetic particles is intergalactic dust. But dust particles aren't able to influence the ultrarelativistic electron (positron or even proton) stream because of its large kinetic energy. That is why there is an only candidate among all capable of fitting all experimental and model data. These are primordial microscopic black holes that are about 40 years have been discussed theoretically, but there is no any explicit experimental evidence for them. Probably, an oblique evidence will be found studying AGN jets on at their final evolution stages. Additional investigations are very necessary and important.

References

[1] Shakura N. I., Sunyaev R. A., Astron. Astrophys. **24**, (1973), 337.

[2] Guerra E. J., Daly R. A., in Accretion Phenomena and Related Outflows, IAU Colloquium 163, eds. Wickramasinghe D. T., Bicknell G. V., Ferrario L. (San Francisco: ASP Conf. Series, 1997), p.695.

[3] Kellermann K. I., Vermeulen R. C., Zensus J. A., Cohen M. H., Astrophys. J. **115**, (1998), 1295.

[4] Walker R. C., Benson J. M., Unwin S. C., Astrophys. J. **316**, (1987), 546.

[5] Hummel C. et al., Astron. Astrophys. **257**, (1992), 489.

[6] Tingay S. J. et al., Nature **374**, (1995), 141.

[7] Mundt R., Brugel E. W., Buhrle T., Astrophys. J. **319**, (1987), 275.

[8] Begelman M. C., Blandford R. D., Rees M. J., Rev. Mod. Phys. **56**, (1984), 255.

[9] Taylor G. B., Perely R. A., Inoue M., Kato T., Tabara H., Aizu K., Astrophys. J. **360**, (1990), 41.

[10] Ulrich M. H., Kinman T. D., Lynda C. R., Rieke G. H., Ekers R. D., Astrophys. J. **198**, (1975), 261.

[11] Takahashi T. et al., Astrophys. J. **470**, (1996), L89.

[12] Kerrick A. D. et al., Astrophys. J. **438**, (1995), L59.

[13] Sembay S., Warwick R. S., Urry C. M., Sokoloski J., George I. M., Makino F., Ohashi T., Tashiro M., Astrophys. J. **404**, (1993), 112.

[14] Kohmura Y., Makishima K., Tashiro M., Ohashi T., Urry C. M., Publ. Astron. Soc. Japan **46**, (1994), 131.

[15] Foster R. S., Waltman E. B., Tavani M., Harmon B. A., Zhang S. N., Paciesas W. S., Ghigo F. D., Astrophys. J. **467**, (1996), L81.

[16] Gammie C.F., McKinney J.C., Astrophys. J. **589**, (2003), 444.

[17] Poplavsky A.L., Dynamics of AGN Jets and Structure of Supermassive Black Hole Magnetospheres. MS Thesis, Belarusian State Uneversity, Minsk, Belarus, (2005), section 3.2.

[18] Bridle A.H., Astron. J. **108**, (1994), 820.