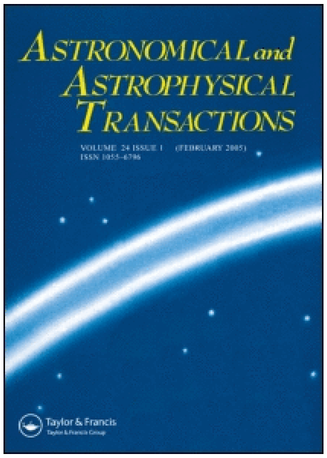

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A. P. Miroshnichenko [a]
[a] Institute of Radio Astronomy, National Academy of Sciences of Ukraine, Kharkov, Ukraine

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Estimates of the jet velocity of quasars and galaxies

A. P. MIROSHNICHENKO*

Institute of Radio Astronomy, National Academy of Sciences of Ukraine, Kharkov, Ukraine

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Several methods for estimating the jet velocity in radio sources are presented. The values of the jet propagation velocities are obtained for a sample of quasars and galaxies on the basis of observed data. The calculated typical jet velocity values are subluminal. The relation between the jet propagation velocities and luminosities in the optical, centimetre and decametre ranges, the redshifts and the linear sizes of radio sources are considered.

Keywords: Jet; Jet propagation velocity; Synchrotron radiation

1. Introduction

The problem of determining the velocity of stream outflows (jets) of quasars and galaxies is important for the physics of radio sources. It has been obtained from very-long-baseline interferometry (VLBI) observations of radio sources that the propagation velocities of jets are subluminal on a parsec scale. The known 'superluminal' velocities as derived for jets of some objects are explained by the relativistic effect when jet motion is oriented close to the line of sight. Characteristic estimates of the propagation velocity of radio lobes formed by jets on their essential deceleration in the extragalactic medium have values of the order of a tenth of the light velocity [1]. In [2] a weak dependence of the propagation velocity of radio lobes on the object's redshift was noted.

A similarity of the jet structures on parsec and kiloparsec scales may testify to the similarity of the propagation velocities of these stream outflows at different distances from the active nucleus objects. Most quasars and galaxies display strongly collimated jets with lengths of the order of dozens of kiloparsecs, indicating the high velocities of these jets. Also the stream outflows on a kiloparsec scale in power sources may have even higher velocities than are found in lower-power sources [2].

*Email: mir@ira.kharkov.ua

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In this paper, we propose several methods for estimating the jet velocities for quasars and galaxies.

2. Methods for estimating the jet velocities of quasars and galaxies

To calculate the jet velocities we used a sample of 46 jet radio sources (33 quasars and 13 galaxies) with the necessary data in the radio and optical ranges. This sample was assembled by us on the basis of observations at 5 GHz [3–5] and at 25 MHz [6, 7], with corresponding optical data [8]. In this paper, the flat model of the Universe with the deceleration parameter $q_0 = 0.5$ and the Hubble constant $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ is applied.

On the assumption of the synchrotron mechanism of radiation of radio sources, we derive estimates of the propagation velocities of the jets of radio sources by several methods.

2.1 *Method 1*

First, with knowledge of the diameter d of the radio source and using an estimate of the characteristic time t_B of synchrotron decay of relativistic particles at the frequency ν, we find the jet velocity v_j from the obvious relation

$$v_\mathrm{j} = \frac{d}{t_B}, \tag{1}$$

where $t_B = (340B^{-3}/\nu)^{1/2}$. We calculate the value of the magnetic field strength B from the generally accepted condition of energy equipartition in radio sources [9]:

$$B = \left(48\,kA(\gamma, \nu)\frac{S_\nu}{r\varphi^3}\right)^{2/7}, \tag{2}$$

where $k = 100$ (proton-to-electron-energy ratio), $A(\gamma, \nu)$ is a tabular function, γ is the index of the electron energy distribution, S_ν is the flux density of the radio source at the frequency ν, R is the distance of the source and φ is the angular dimension of the source. Estimates of the mean velocity of jets obtained by equation (1) are as follows:

(i) For objects of the whole given sample ($n = 46$), $\langle v_\mathrm{j}\rangle = 1.57 \times 10^{10} \pm 5.20 \times 10^9\ \mathrm{cm\,s^{-1}}$.
(ii) For sample quasars ($n = 33$), $\langle v_j\rangle_\mathrm{Q} = 1.99 \times 10^{10} \pm 7.10 \times 10^9\ \mathrm{cm\,s^{-1}}$.
(iii) For sample galaxies ($n = 13$), $\langle v_j\rangle_\mathrm{G} = 4.99 \times 10^9 \pm 2.14 \times 10^9\ \mathrm{cm\,s^{-1}}$.

2.2 *Method 2*

Let us suppose that the luminosity L_j of the jet has a comparable value with the corresponding kinetic luminosity L_k of the jet, *i.e.* $L_\mathrm{j} \approx L_\mathrm{k}$. The value of L_j can be expressed as [10]

$$L_\mathrm{j} = (U + P)\frac{V}{\tau}, \tag{3}$$

where U is the energy density of the relativistic plasma, $3P = U$ (where P is the pressure) and V/τ is the time rate of change in the volume of jet (which may be written as $\pi r_j^2 v_j$, where r_j is the jet radius).

Then,

$$L_j = \frac{4}{3}\pi r_j^2 v_j U, \tag{4}$$

where $U = (7/3)B^2/8\pi$, where B is the magnetic field strength of radio source.

The value of the kinetic luminosity L_k can be written as the rate of change in the kinetic energy of the jet:

$$L_k = \frac{\pi r_j^2 \rho_j v_j^3}{2}, \tag{5}$$

where ρ_j is the jet density.

So, we have the estimate of the jet velocity v_j from equations (4) and (5) and define it as v_{jk}:

$$v_{jk} = \left(\frac{7}{\pi\rho_j}\right)^{1/2} \frac{B}{3}. \tag{6}$$

We suppose throughout this paper that the value ρ_j equals 10^{-25} g cm^{-3}. By this method we determined from our sample the following results.

(i) For the whole sample ($n = 46$), $\langle v_{jk}\rangle = 1.88 \times 10^{10} \pm 1.40 \times 10^{10}$ cm s^{-1}.
(ii) For sample quasars ($n = 33$), $\langle v_{jk}\rangle_Q = 2.53 \times 10^{10} \pm 1.95 \times 10^{10}$ cm s^{-1}.
(iii) For sample galaxies ($n = 13$), $\langle v_{jk}\rangle_G = 2.15 \times 10^9 \pm 1.56 \times 10^9$ cm s^{-1}.

2.3 *Method 3*

Let us consider the total luminosity L_t of the radio source, corresponding to a certain magnetic field with strength B:

$$L_t = c\pi r_j^2 B^2. \tag{7}$$

On the assumption that this value is close to the kinetic luminosity L_k, *i.e.* $L_t = L_k$, we derive from equations (5) and (7) the estimate of the jet velocity, defined as v_{jt}:

$$v_{jt} = \left(\frac{2cB^2}{\rho_j}\right)^{1/3}. \tag{8}$$

For our sample, this method gives the following values for the mean velocity of jets.

(i) For the whole sample ($n = 46$), $\langle v_{jt}\rangle = 4.62 \times 10^9 \pm 2.25 \times 10^9$ cm s^{-1}.
(ii) For sample quasars ($n = 33$), $\langle v_{jt}\rangle_Q = 5.82 \times 10^9 \pm 3.11 \times 10^9$ cm s^{-1}.
(iii) For sample galaxies ($n = 13$), $\langle v_{jt}\rangle_G = 1.60 \times 10^9 \pm 7.28 \times 10^8$ cm s^{-1}.

2.4 *Method 4*

Since a jet is the plasma stream propagating in a magnetic field, the propagation velocity of the relativistic electrons of a jet may be close to the Alfvén velocity, v_A:

$$v_A = \frac{B}{(4\pi\rho_j)^{1/2}}. \tag{9}$$

So, the estimates of the mean jet velocity obtained from equation (9) are as follows.

(i) For the whole sample ($n = 46$), $\langle v_A \rangle = 1.06 \times 10^9 \pm 7.95 \times 10^8\ \mathrm{cm\,s^{-1}}$.
(ii) For sample quasars ($n = 33$), $\langle v_A \rangle_Q = 1.43 \times 10^9 \pm 1.11 \times 10^9\ \mathrm{cm\,s^{-1}}$.
(iii) For sample galaxies ($n = 13$), $\langle v_A \rangle_G = 1.22 \times 10^8 \pm 8.83 \times 10^7\ \mathrm{cm\,s^{-1}}$.

2.5 *Method 5*

The VLBI observations of radio sources make it possible to determine the spectral indices for different parts of the jets. For example, there are spectral indices α_0 and α for the two parts of the given jet that have a relative separation Δr. We suppose that the change in the spectral index from α_0 to α in the frequency range from ν_1 to ν_2 is due to the synchrotron decay of relativistic electrons for a time t of propagation of the jet over the distance Δr.

We use the relation for the change in the spectral index in a jet due to synchrotron losses [11]:

$$\alpha = \alpha_0 + \frac{\gamma_0 - 2}{\ln(\nu_2/\nu_1)} \ln\left(\frac{1 - \mu B^2 E_1 t}{1 - \mu B^2 E_2 t}\right), \tag{10}$$

where $\gamma_0 = 2\alpha_0 + 1$, $\mu = 1.57 \times 10^{-3}$ and $E_i = (\nu_i / 1.41 \times 10^{18} B)^{1/2}$.

We derived from equation (10) the relation for the corresponding time $t = t_\alpha$:

$$t_\alpha = \frac{(\nu_2/\nu_1)^{(\alpha-\alpha_0)/(2\alpha_0-1)} - 1}{\mu B^2 [E_2 (\nu_2/\nu_1)^{(\alpha-\alpha_0)/(2\alpha_0-1)} - E_1]}. \tag{11}$$

Using the value t_α we estimate the jet velocity $v_{j\alpha}$ corresponding to the change in the spectral index in the jet:

$$v_{j\alpha} = \frac{\Delta r}{t_\alpha}. \tag{12}$$

We determine the value $v_{j\alpha}$ from equation (12) for some radio galaxies with known spectral index distributions, namely 3C405 [12], 3C218 [13] and 3C303 [14]. It is known that the sources 3C405 and 3C218 are powerful elliptical galaxies, and that 3C303 is an N-type galaxy (galaxies of N type have properties close to those of quasars). So, the jet velocity estimates found by this method are as follows: $v_{j\alpha} \approx 10^{10}$ cm s^{-1} (3C405), $v_{j\alpha} \approx 10^8$ cm s^{-1} (3C218) and $v_{j\alpha} \approx 10^9$ cm s^{-1} (3C303).

3. Relationship between the jet velocity and some parameters of the radio source

It is of interest to examine the relationship between the jet velocity and the physical characteristics of the radio source. For the sample quasars and galaxies we consider the jet velocities (relative to the light velocity c) versus the redshifts, luminosities and radii of radio sources. Note that all the considered methods of jet velocity estimates show correlations analogous to those presented in figures 1– 5 (for the velocity estimates obtained by method 2). The jet velocities positively correlate with the redshifts of the radio sources. As one can see from these figures, the jet velocity increases with increasing luminosity in different frequency ranges (in the optical range, at 5 GHz and at 25 MHz). Note that the jet velocities strongly correlate with the linear sizes (radii) of the radio sources. The value of the jet velocity increases for more compact sources (see figure 5) with high coefficients of correlation (about 0.9), in particular for quasars.

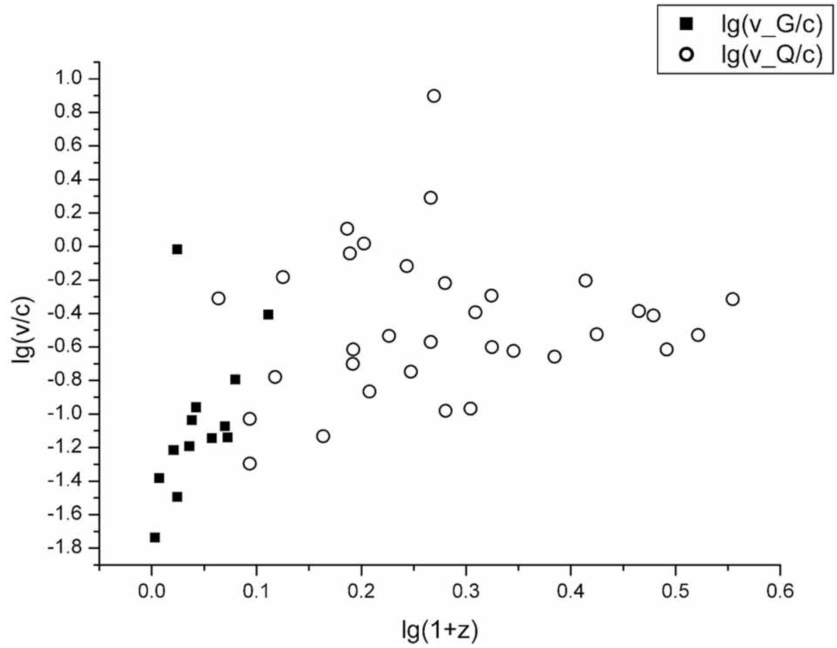

Figure 1. Jet velocity versus the redshift.

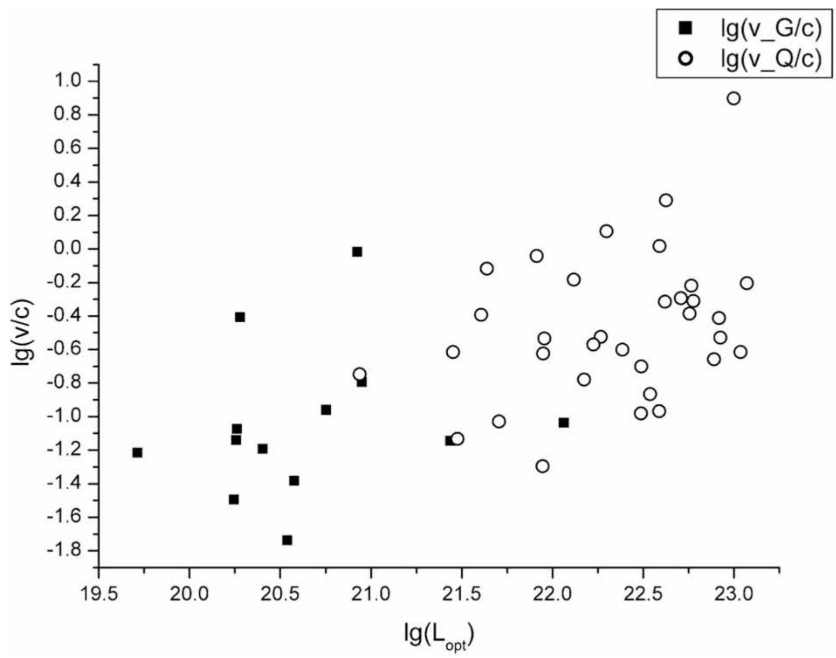

Figure 2. Jet velocity versus the observed optical luminosity.

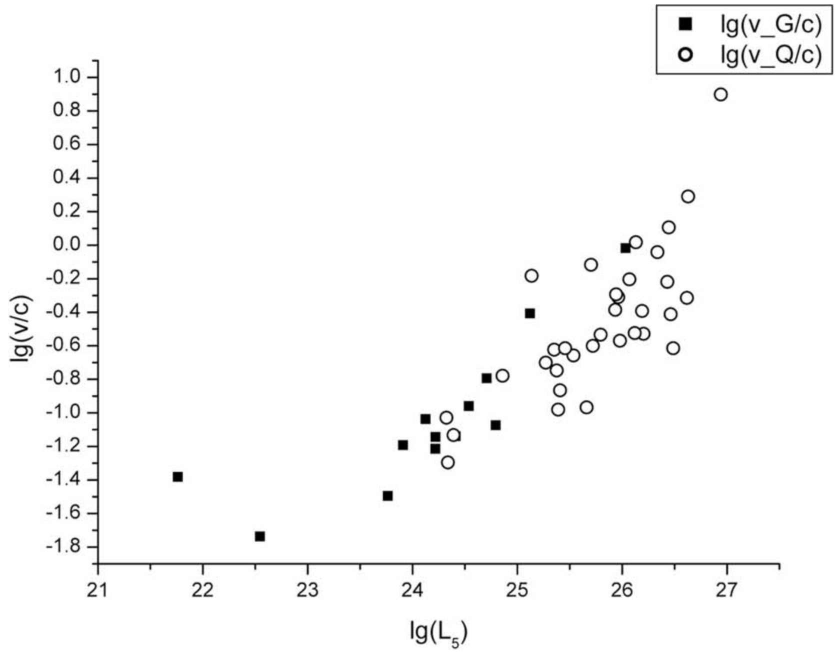

Figure 3. Jet velocity versus the observed luminosity at 5 GHz.

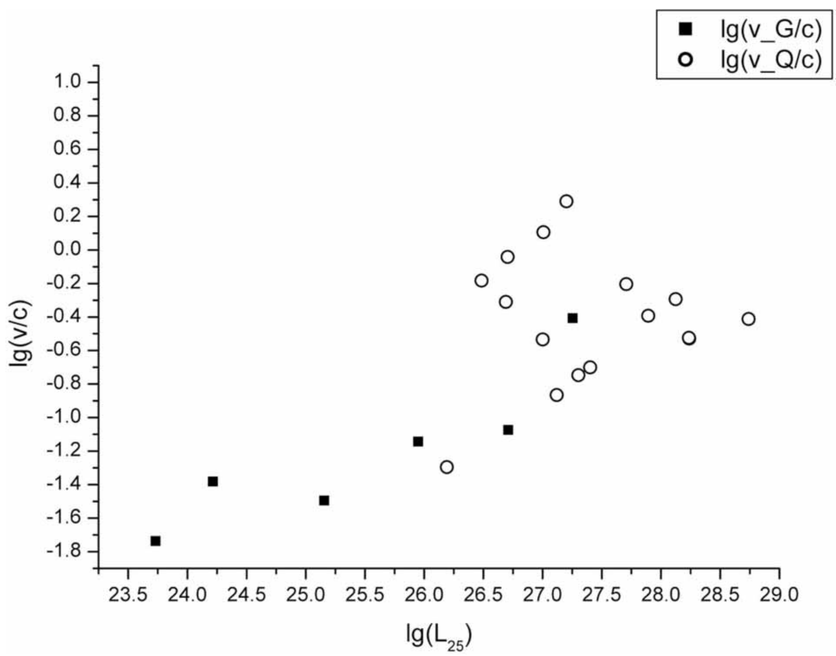

Figure 4. Jet velocity versus the observed luminosity at 25 MHz.

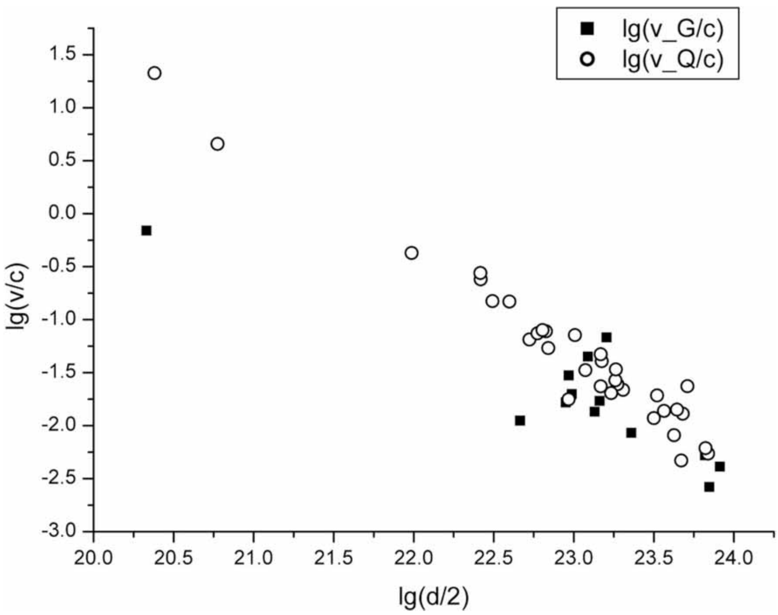

Figure 5. Jet velocity versus the radius of the radio source.

4. Conclusion

As estimated by several methods for quasars and galaxies, the typical values of the jet propagation velocities are subluminal. The velocity of jet propagation strongly correlates with the linear size and luminosity of a radio source in different frequency ranges, and it also correlates with the redshift of a radio source, in particular for galaxies. So, the derived relationships provide evidence that younger radio sources (which are more luminous and more compact, and often at higher redshifts) have higher velocities of jet propagation.

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