Astron. Astrophys. 224, 24–30 (1989)

ASTRONOMY AND ASTROPHYSICS

Two-fluid model of superluminal radio sources: application to cosmology

G. Pelletier[1] **and J. Roland**[2,3]

[1] Observatoire de Grenoble, Groupe d'Astrophysique UA 708, CERMO, BP 68, F-38402 St-Martin d'Hères Cedex, France
[2] Sterrewacht, Postbus 9513 NL-2300 RA Leiden, The Netherlands
[3] Institut d'Astrophysique de Paris, CNRS 98bis, Bd Arago, F-75014 Paris, France

Received January 31, accepted March 1, 1989

Summary. Superluminal sources associated with strong double radio sources with hot spots in extended lobes can be explained by a two-fluid model having:

i) a *non-realistic jet* of $e^- - p$ plasma with velocity $v_j \simeq 0.35\,c$, which carries most of the mass and kinetic power of the flow. When this jet interacts with the intergalactic medium, it forms hot spots in the extended lobes.

ii) a *relativistic beam* of $e^- - e^+$ plasma with velocity $v_b \simeq c$, moving in a channel through the jet.

iii) a magnetic field parallel to the jet and the beam which stabilizes the beam against Kelvin-Helmoltz instabilities and avoid the development of a strong dissipation through Langmuir turbulence.

The beam and the jet interact at the surface and at the end of the channel. Blobs moving in the channel are the *radio knots* moving relativistically.

Observations of two velocities in the VLBI jet of NGC 1275 and of the limb brightening of the VLBI jet of M 87 support the two-fluid model even though these sources are not superluminal.

The ejection of material at relativistic velocities by the nuclei of strong double radio sources allows us to determine of the cosmological parameters q_0 and H_0 independently of any luminosity calibration. Published data do not yet allow the determination of q_0. However, by adopting $q_0 = 1/2$, with existing data we find the Hubble constant is $H_0 \simeq 100 \pm 30$ km s^{-1} Mpc^{-1}. Observation of strong double radio sources with two-sided VLBI jets, or with large angular sizes, will fix H_0 in a near future.

Key words: Superluminal radio galaxies – two-fluid jets – cosmology

1. Introduction

Shklovsky (1963, 1965) suggested that relativistic beaming might explain the asymmetric structure of M 87 and 3C 273. After the discovery of the variability of compact radio sources in nuclei of galaxies, Rees (1966, 1967) proposed a relativistic ejection from nuclei of galaxies. The appearance, time variation and spectral behavior of two sources separating at relativistic velocity were studied by Ozernoi and Sazonov (1969). Some years later, superluminal radio sources and jets were discovered, and X-ray observations showed no inverse Compton catastrophe in variable compact radio nuclei of galaxies, giving further evidence for relativistic beaming. The concept of relativistic jets to supply energy to the Cygnus A hot spots was introduced by Scheuer (1974) and Blandford and Rees (1974). The simplest model for superluminal radio sources is that of a relativistic jet all the way from the nucleus to the extended lobe (Scheuer and Readhead, 1979; Blandford and Königl, 1979). Properties of superluminal radio sources are given by Kellermann and Pauliny-Toth (1981), Cohen (1986), and Pearson and Zensus (1987).

The observations of superluminal radio sources can be understood by supposing that the relativistic electrons responsible for the synchrotron emission of VLBI jets are moving with a mean Lorentz factor $3 \leq \gamma \leq 10$ at an angle $\theta \simeq 1/\gamma$ with the line of sight.

The apparent transverse velocity v_{ap} of an object, with a low redshift, moving with the true velocity v is $v_{ap} = v \sin\theta / (1 - (v/c)\cos\theta)$ where θ is the angle between the motion and the line of sight (Ginzburg and Syrovatskii, 1969). Moreover, the radiation of the VLBI jet is no longer isotropic, but is beamed along the direction of motion within an angle of halfwidth $\sim 1/\gamma$. The apparent flux density of a moving component, $S(\theta)$, in terms of the flux density, S_0, of the same component at rest, is given by $S(\theta) \sim \gamma^3 S_0$ when $\theta \leq 1/\gamma$ (Ryle and Longair, 1967).

However, VLBI observations do not imply that the thermal component of the VLBI jet is also moving relativistically, i.e., its velocity can be $v < c/\sqrt{3}$ and it can therefore be described with non relativistic hydrodynamics. Consequently, to understand superluminal sources we have to try to first answer three questions:

i) What is the velocity of the thermal plasma is the VLBI jet?

ii) What is the ratio of the kinetic power of the thermal component $P_{K,th}$ to the kinetic power $P_{K,re}$ of the relativistic electrons moving with a Lorentz factor $\gamma \leq 10$?

iii) What is the ratio of the energy density of the thermal component W_{th}, to the energy density of the relativistic electrons W_{re}?

The answers to these three questions provide the crucial constraints to models of superluminal radio sources and to models of jet formation in nuclei of galaxies.

A large fraction of superluminal sources are associated with strong double radio sources (Table 1). These sources have hot spots similar to those of Cygnus A, which allow us to determine the velocities and the kinetic energies of their thermal components.

Section 2 gives the characteristics of jets powering hot spots similar to those of Cygnus A. Section 3 describes the jets of

Send offprint requests to: J. Roland (Paris)

Table 1. Superluminal radio sources associated with strong double radio galaxies

Source name	Position	Comments	References
3C 111	04 15+379	Possibly superluminal	(3)
3C 120	04 30+052	Complex double	(13)
3C 147	05 38+498		(4)
3C 179	07 23+679		(5)
08 50+581			(1), (6)
3C 216	09 06+430		(1), (6)
4C 39.25	09 23+392		(7), (8)
3C 245	10 49+123		(9)
3C 263	11 37+660		(1)
3C 279	12 53−055		(10)
3C 345	16 41+399		(1)
16 42+690			(1)
4C 34.47	17 21+343		(11)
3C 390.3	18 45+797		(12)
3C 395	19 01+319	Possible double	(1)
19 28+738			(14)

References: (1) Browne (1987), (3) Götz et al. (1987), (4) Conway (1988), (5) Shone et al. (1985), (6) Pearson et al. (1987), (7) Shaffer and Marsher (1987), (8) Browne et al. (1982), (9) Hough and Readhead (1987), (10) Unwin (1987), (11) Bartel et al. (1989), (12) Alef et al. (1988), (13) Walker et al. (1987), (14) Simon et al. (1987).

superluminal radio sources with a two fluid model. Section 4 discusses the consequences of our model and the possibility of deriving the cosmological parameters q_0 and H_0.

2. Characteristics of the jets powering hot spots similar to those of Cygnus A

Although Cygnus A is not a superluminal source, data concerning the hot spots, the extended lobes and the intergalactic medium are good enough to obtain the determination of the physical parameters of the radio plasma in hot spots and of the jet powering them. Moreover, hot spots of superluminal radio sources associated with strong double radio galaxies have the same characteristics as those in Cygnus A. Thus the study of Cygnus A hot spots (Roland et al., 1988) allows us to model superluminal radio sources in strong double radio galaxies.

Hot spots are due to the interaction of a supersonic jet with the intergalactic medium, and are thought to be the downstream flow behind the strong shock at the end of the jet. We found (Muxlow et al., 1988), assuming for the Hubble constant the value $H_0 \simeq 50$ km s^{-1} Mpc^{-1}, that the speed of advance v_{sep} of the Cygnus A hot spots in the intergalactic medium is $0.022c \leq v_{sep} \leq 0.063c$. Moreover, we showed that as long as $v_{sep} \leq 0.088c$, the hydrodynamics are non relativistic. Adopting $v_{sep} \simeq 0.05\ c$ in agreement with radio observations, we found (Roland et al., 1988) that the density of the thermal component inside the hot spots is $n \simeq 1.1\ 10^{-3}\ e^-$ cm^{-3}. From the 151 MHz map of Cygnus A (Leahy et al., 1989), we derived the velocity of the thermal flow in the VLBI jet to be $v_j \simeq 0.35\ c$. Thus the mass ejected by the nucleus to power one jet is $\dot{M}_j \simeq 2.5\ M_\odot$ yr^{-1} and the kinetic power of the thermal flow is $P_{K,th} \simeq 9.5\ 10^{45}$ erg s^{-1}. The integrated luminosity of one hot spot is $L_s \simeq 2.8\ 10^{44}$ erg s^{-1}, or 3% of the kinetic power of the thermal flow. As the radio luminosity of the jet is small compared with the luminosity of one hot spot, from the conservation of the mass flux, we found that the velocity of the thermal flow must be constant along the jet.

From VLBI observations of Cygnus A, we found in the VLBI jet that the ratio N_{re}/N_{th} is $N_{re}/N_{th} \simeq 3.8\ 10^{-4}$ where N_{re} is the number of the relativistic electrons and N_{th} the number of the electrons of the thermal component. If the relativitic electrons have a mean velocity characterized by a Lorentz factor $\gamma \simeq 10$, the kinetic power of the relativistic flow is $P_{K,re} \simeq 8.9\ 10^{41}$ erg s^{-1}, about 10^4 times lower than the kinetic power of the thermal component. Moreover, supposing that the Mach number of the VLBI jet was $M \simeq 10$, we found that the energy density of the thermal component W_{th} dominates, i.e. $W_{th} \simeq 30\ W_{re}$ and $W_{re} \approx W_m$, where W_{re} and W_m are the energy densities of the relativistic electrons and of the magnetic field.

So we concluded that *hot spots are due to the interaction of the thermal component of a supersoinic jet with the intergalactic medium and that the kinetic power of the jet and its hydrodynamic is governed by its thermal component.*

We are now ready to explain superluminal radio sources in strong double radio galaxies.

3. Characteristics of jets of superluminal radio sources associated with strong double radio galaxies

3.1. The two-fluid jet model

Superluminal radio sources and hot spots associated with their extended lobes can both be explained if the jet in the nucleus of the galaxy contains two fluids:

i) a *non-relativistic jet* of electron-proton plasma which carries most of the mass and kinetic energy. We will call this the *thermal component* or the *jet*. It carries $\dot{M} \simeq 2.5\ M_\odot$ yr^{-1} at a velocity $v_j \simeq 0.35\,c$. Its kinetic power is $P_{\mathrm{K,th}} \simeq 10^{46}$ erg s^{-1}, and it is responsible for the formation of hot spots in the extended lobes. The integrated luminosity of one hot spot is $L_{\mathrm{HS}} \simeq 3\,10^{44}$ erg s^{-1}, or 3% or the kinetic power of the jet.

ii) a *relativistic flow* of electron-positron plasma with a particule number 10^{-4} times lower than the number of particles of the thermal jet. It is moving in a channel through the jet and we call it the *beam*. Its mean velocity has a Lorentz factor $\gamma_b \simeq 10$, and its kinetic power is $P_{\mathrm{K,re}} \simeq 10^{42}$ erg s^{-1}.

iii) the magnetic lines of force are parallel to the flow, and close to the nucleus in the VLBI jet, we have $W_{\mathrm{th}} \gg W_{\mathrm{re}} \approx W_{\mathrm{m}}$.

A two-fluid model, supposing a relativistic $e^- - e^+$ plasma pervading the classical jet, instead of a relativistic beam moving in a channel, has been proposed by Sol et al. (1989) to explain the superluminal radio source 3C 120.

The detections of two different velocities in the VLBI jet of NGC 1275 (Maar et al., 1988) and of the limb brightening of the VLBI jet of M 87 (Reid et al., 1989) support the two-fluid model even though these two sources are not superluminal.

As long as the dynamical pressure of the relativistic beam is greater than the pressure of the thermal medium, W_{th}, the beam digs a channel in the jet. This happens if

$$n_b \gamma_b^2 m_e c^2 \geq W_{\mathrm{th}}. \quad (1)$$

For the VLBI jet of Cygnus A, the energy density of the thermal flow is $W_{\mathrm{th}} \simeq 6\,10^{-4}$ erg cm^{-3} and then $n_b \geq 7\,e^-$ cm^{-3}. Moreover, with $n_j \simeq 330\,e^{-1}$ cm^{-3}, $n_b \simeq 7\,e^-$ cm^{-3} and $N_b/N_j \simeq 4\,10^{-4}$, we estimate the radius of the beam to be

$$R_b \simeq R_j (4\,10^{-4}\,n_j/n_b)^{1p2} \leq 0.14\,R_j, \quad (2)$$

i.e., with a jet radius $R_j \simeq 1$ pc, we find that the radius of the beam is $R_b \simeq 0.1$ pc. The same result can be obtained writing that the thermal pressures of the beam and of the jet are equal.

VLBI polarization observations (Wardle and Roberts, 1988) constrain the two-fluid model. In the source OJ 287, the percentage polarization of the jet reached 64% in 1982, indicating that the relativistic $e^- - e^+$ flow was a pure, unmixed beam inside the jet. In other sources, the percentage of polarization is high, about 10–20%, but smaller than in the jet of OJ 287 in 1982. This indicates some depolarization probably due to the mixing of the relativistic plasma with the thermal flow at the surface of the beam rather than a chaotic magnetic field, because a low level of MHD turbulence is expected in these jets.

The interaction of the beam and the jet at the surface of the beam produces a limb brightening of the VLBI jet, as observed for the subluminal radio surface M 87 by Reid et al. (1989). In strong double radio sources, when the ejection of the $e^- - e^+$ plasma varies with time, higher density blobs of $e^- - e^+$ move relativistically in the channel, and the observed radio knots are due to either higher densities of $e^- - e^+$, or to the interaction of the blob with the surface of the channel. These radio knots move relativistically, producing superluminal sources.

3.2. Stability and dissipation of the two fluids

The relativistic $e^- - e^+$ beam flows along magnetic field lines, and can be stable against Kelvin-Helmoltz perturbations. The stability condition is

$$B > (2\pi n_b \gamma_b^2 m_e c^2)^{1/2}. \quad (3)$$

This implies $B > 6\,10^{-2}$ G for a typical value of $n_b \simeq 7\,e^-$ cm^{-3}.

If the beam is sporadic, the channel remains empty for a long time because the fastest diffusion process, namely Bohm diffusion, has a very long diffusion time, $\tau \simeq R_b^2/D$, where R_b is the beam radius and D the Bohm diffusion coefficient.

We note that blobs of small length will not experience Kelvin-Helmoltz instability.

We examine now boundary layers where the two flows interpenetrates, as suggested by VLBI polarization observations, the core of the beam being a pure $e^+ - e^+$ plasma.

As shown in Pelletier et al. (1988), if the magnetic field is greater than some critical value B_c, a relativistic $e^- - e^+$ beam can propagate along the magnetic field lines which are parallel to a non-relativistic $e^- - p$ jet. The critical field is obtained when $\omega_{ce} = \omega_p$ where ω_{ce} is the cyclotron frequency of the electrons and ω_p is the plasma frequency, i.e. if

$$B > B_c = (4\pi n_{\mathrm{th}} m_e c^2)^{1/2}, \quad (4)$$

where n_{th} is the density of the thermal plasma in the mixing layer. With $n_{\mathrm{th}} \simeq 330\,e^-$ cm^{-3}, the critical value of the magnetic field is $B_c \simeq 6\,10^{-2}$ G on the surface of the channel. Thus when the magnetic field is greater than B_c, the jet is also stable to Kelvin-Helmoltz perturbations. Note that this value corresponds to a jet near the nucleus, at large distances the critical value for the magnetic field is lower.

When the beam pervades the thermal medium, one can worry that it relaxes on a short scale, mostly because of the fast excitation of plasma waves, especially the electrostatic Langmuir waves at the narrow resonance $\omega_p = kc$. However it has been shown by Pelletier et al. (1988) that, under conditions that seem to be widely satisfied in the situation we investigate (Sol et al., 1989), the beam instability saturates in the form of a set of solitary waves packets suffering a weak dissipation as long as $B > B_c$. When the magnetic field is strong, the electron dynamics is quasi one-dimensional and give rise to solitons corresponding to a stable balance between dispersion and non-linear wave compression. These quasi one-dimensional structures are stable to transverse perturbations when $B > B_c$, and the shortest wavelength of the wave packet is large compared to the Debye length, characteristic of the Landau absorption.

When the jet opens the magnetic field becomes smaller than B_c, the electron dynamics loose their one-dimensional character and the solitary waves are no more stable solitons, but become collapsing wave packets that transfer energy to suprathermal electrons through Landau absorption at a high rate. We do not expect that the beam pervades the thermal jet beyond that critical region; however, as shown in Sol et al. (1989), this region could be as far as one kpc.

An interesting aspect of the interaction region is the current generation (Sol et al., 1989) that could explain the magnetic features of the VLBI blobs. Indeed, during its relaxation via Langmuir turbulence, the beam transfer momentum to the thermal electrons component of the jet; which produces a current limited by the anamalous resistivity. If the jet is MHD confined, this current increases significantly the poloïdal current that produces the confining toroïdal magnetic field, surrounding the beam. So, in that interaction region, the field lines could appear mostly perpendicular to the flow, and then becomes again parallel to the flow when the blob as gone. The interaction is able to recollimate locally the flow. Faraday rotation due to the thermal component, or changing relativistic aberration can also modify the direction of the observed magnetic field in radio knots.

In front of the beam in the region where the two flows interpenetrate, a front of interaction takes place, and the relativistic fluid dissipates via strong Langmuir turbulence which accelerates relativistic electrons and a bright radio knot appears in the jet. The knot at 4″ from the nucleus of 3C 120 can be an example of such dissipation area and has been studied by Sol et al. (1989). The disspation area moves along the jet and observations of Walker et al. (1988) can be explained if the brightness surface of the knot change with time, which is expected when the relativistic fluid disspates. But this dissipation does not disturb the hydrodynamics of the thermal component, which carries most of the kinetic power of the jet.

4. Dicsussion and application to cosmology

4.1. Comparison with previous relativistic models

The main differences between the two-fluid model and previous relativistic models are:

i) In the two-fluid model, most of the jet mass and kinetic energy are associated with the thermal component moving at non-relativistic speed, $v_j \simeq 0.35\ c$. The mass loss of the relativistic ejection is low, i.e. about $10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, while the non-relativistic jet carries about $2.5\ M_\odot\ \mathrm{yr}^{-1}$.

ii) The formation of a two fluid jet is energetically easier than the formation of a single relativistic jet with a Lorentz factor $\gamma \simeq 10$.

Indeed, the formation of the thermal flow with $v_j \simeq 0.35\ c$ can probably be explained by the MHD extraction process proposed in 1961 by Mestel and developed later (see e.g. Mestel, 1961; Blandford and Payne, 1982; Draine, 1983; Pudritz and Norman, 1983; Ushida and Shibata, 1985, and others).

The relativistic $e^- - e^+$ beam can be created in the funnel close to the black hole with a Lorentz factor $\gamma_b \simeq 10$ (Phinney, 1987).

4.2. Relation of VLBI jets to large scale jets

The relativistic fluid carries a small fraction of the kinetic energy of the jet. Thus VLBI observations show only a small fraction of the energy ejected by the nucleus. In a source like Cygnus A, the one-sided VLBI structure is not due to Doppler beaming if the jets are perpendicular to the line of sight, but is due to a small difference in the intensity of the two beams. One beam contains a higher fraction of $e^- - e^+$ than the other, but the kinetic energy of the invisible, non-relativistic components in the two jets are the same, as shown by the symmetric hot spots in the extended lobes. Relativistic $e^- - e^+$ in VLBI jets lose energy through radiative processes. However, their energy is greater than the threshold energy for reacceleration by weak oblique shocks in the large-scale jet, and consequently the large-scale jet on the same side as the VLBI jet is brighter than the counter-jet on the other side.

4.3. Relativistic ejections in strong double radio sources

An important prediction of the two-fluid jet model is that most strong double radio sources with hot spots in extended lobes, have relativistic $e^- - e^+$ beams at least on one side or probably on both sides close to the nucleus. As long as the magnetic field in the VLBI jet is exceeds the critical value, the relativistic $e^- - e^+$ plasma propagates with $v \simeq c$. So relativistic motions should be observed in strong radio galaxies even if the jets are perpendicular to the line of sight. In fact, relativistic motions in strong extragalactic radio sources seem to be frequent (Witzel et al., 1988).

4.4. Application to cosmology

If strong double radio sources have relativistic ejections, then it is possible to deduce the cosmological parameters q_0 and H_0 independently of any luminosity calibration. Indeed, when a source has jets perpendicular to the line of sight, measurement of the real motion of the material ejected at the speed of light, is a way to determine these fundamental parameters of the geometry of the Universe.

The method we propose here is different from the method of Lynden–Bell (1977).

Let us suppose that the beam has a real motion with a velocity close to that of light perpendicular to the line of sight. If $\gamma_b \geq 3$, its velocity is within 6% of c.

The angular size of an object emitting at time t a radiation received at time t_0 is related to its size l perpendicular to the line of sight by a formula of the form $\theta = (H_0 l/c) f(q_0, z)$, where the function $f(q_0, z)$ is given by Weinberg (1972). Thus, for a real motion perpendicular to the line of sight, $dl = v\,dt$, the observed angular velocity $\mu_\perp(z)$ is given by $\mu_\perp(z) = (d\theta/dt_0) = (d\theta/dt)/(1+z)$ and we obtain with $\beta = v/c$.

$$\mu_\perp(z) = H_0 \beta (1+z) q_0^2 / [q_0 z + (q_0 - 1)((1 + 2q_0 z)^{1/2} - 1)]. \tag{5}$$

The main problem is to select properly relativistic motions in jets perpendicular, or nearly perpendicular to the line of sight. Considers a sample of strong double radio sources at the same redshift with two-sided VLBI jets or with large angular sizes.

If one considers only strong double radio sources with two-sided VLBI jets, one can discriminate against receding jets that would have apparent subluminal velocities. Moreover, strong double radio sources with large angular sizes are presumed to be perpendicular to the line of sight. So, in such a sample, one can select jets with knots moving with an apparent motion close to their real motion, i.e., with light velocity.

Among the jets moving towards the observer, few of them have apparent subluminal velocities if the angle θ is smaller than $1/(2\gamma^2)$. This angle is so small that it is difficult to observe any apparent motion, and this type of object might be identified by their strong Doppler amplification. Apart from these rare jets, the others, at oblique angles, have an apparent velocity greater than c. However, those moving perpendicularly to the line of sight that have the smallest apparent velocity and are of cosmological interest.

Thus, from our sample of radio sources at a given redshift, the apparent motion μ of the ejected plasma is greater or equal to the real motion corresponding to an ejection perpendicular to the line of sight $\mu_\perp$, i.e.

$$\mu(z) \geq \mu_\perp(z). \tag{6}$$

If we select from a large sample of strong double radio sources, subsamples with different redshifts, say $z \simeq 0.5$, $z \simeq 1.5$ and $z \simeq 2$, then for each subsample we have $\mu(z) \geq \mu_\perp(z)$ and comparison of $\mu_\perp$ of the different subsamples allows the determination of q_0.

Indeed,

$$\mu_\perp(z_2)/\mu_\perp(z_1) = F(q_0, z_1, z_2). \tag{7}$$

When $q_0 > 0$, one has

$$F(q_0, z_1, z_2) = \left(\frac{1+z_2}{1+z_1}\right) \frac{q_0 z_1 + (q_0 - 1)[(1+2q_0 z_1)^{1/2} - 1]}{q_0 z_2 + (q_0 - 1)[(1+2q_0 z_2)^{1/2} - 1]}, \tag{8}$$

or, when $q_0 = 0$, $F(0, z_1, z_2)$ is given by

$$F(0, z_1, z_2) = \left(\frac{1+z_2}{1+z_1}\right) \frac{z_1(1+z_1/2)}{z_2(1+z_2/2)}. \tag{9}$$

(7) may be solved to get q_0, and then the parameter H_0 can be obtained from (5)

$$H_0 = \frac{\mu_\perp(z)}{\beta} \frac{q_0 z + (q_0 - 1)[(1+2q_0 z)^{1/2} - 1]}{q_0^2(1+z)}. \tag{10}$$

4.5. Comparison with observations

VLBI observations of complete samples of strong double radio sources have recently started (Pearson and Readhead, 1988; Hough and Readhead, 1989). We now use published observations of $\mu(z)$ (Cohen et al., 1988) to show how to apply the method. Figure 1 shows the observed apparent motions, $\mu(z)$, from Cohen et al. (1988). Upper limits which do not correspond to any observed apparent motions are not been plotted.

A source of special interest is the very extended quasar 4C 34.47 where superluminal motions have been observed.

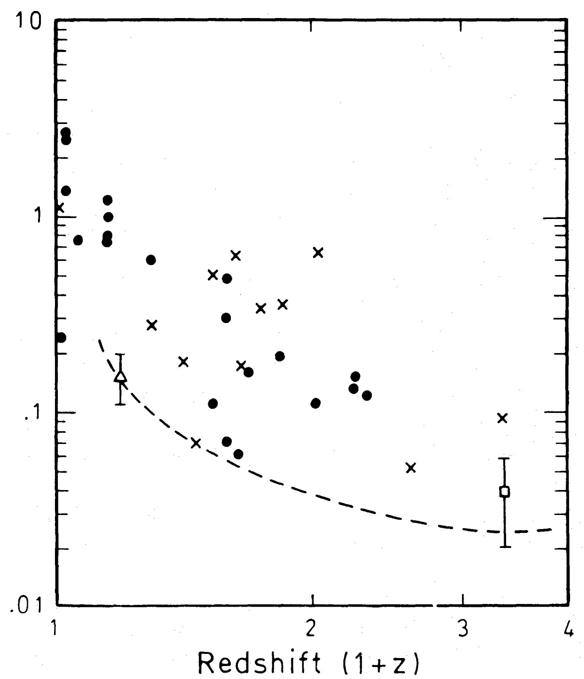

Fig. 1. Apparent motions in nuclei of galaxies. Apparent motions $\mu(z)$ published by Cohen et al. (1988). The upper limits have been excluded. The filled circles represent sources with well established measurements and the crosses represent sources with only limited observations. The triangle and the square are associated with 4C 34.47 and DA 193, which apparent motions are respectively $\mu \simeq 0.15 \pm 0.04$ m.a.s yr^{-1} and $\mu \simeq 0.04 \pm 0.02$ m.a.s. yr^{-1}. The dashed line corresponds to $\mu_\perp(z)$ for $H_0 \simeq 100$ km s^{-1} Mpc^{-1} and $q_0 = 1/2$

Supposing that component A is related to the nucleus of the galaxy, Barthel et al. (1989) find that the apparent motion of component B is $\mu_B \simeq 0.15 \pm 0.04$ m.a.s. yr^{-1} and the apparent motion of component C is $\mu_C \simeq 0.29 \pm 0.02$ m.a.s. yr^{-1}. Barthel et al. (1985) interpreted the VLBI structure of 4C 34.47 as a two-sided jet. Since the apparent motion of C is twice the apparent motion of B, it is more likely that component B is the nucleus, with components A and C moving in opposite directions with the same apparent motions, $\mu \simeq 0.15$ m.a.s. yr^{-1}. We adopt this interpretation, and plot the corresponding point in Fig. 1 with a triangle. This very extended quasar is probably perpendicular to the line of sight and its redshift is $z \simeq 0.206$.

Charlot (1989) observed an apparent motion $\mu \simeq 0.04 \pm 0.02$ m.a.s. yr^{-1} in DA 193 which redshift is $z \simeq 2.365$. The corresponding point has been plotted with a square in Fig. 1.

Cohen et al. (1988) note that their sample is not a complete sample of strong double radio sources, and they have few sources aligned perpendicular to the line of sight. However, the subsample corresponding to $z \simeq 0.5$ seems reasonably good and we have $\mu_\perp(z \simeq 0.5) \simeq 0.06$ m.a.s. yr^{-1}. At high redshift few sources are known, and with the available data, one cannot obtain q_0. We therefore plotted in Fig. 1 the dashed line corresponding to $\mu_\perp(z)$ for $H_0 \simeq 100$ km s^{-1} Mpc^{-1} and $q_0 = 1/2$, as an example.

If the actual data are too poor to obtain q_0, one can still estimate H_0, supposing $q_0 = 1/2$. From the $z \simeq 0.5$ subsample, $\mu_\perp(0.5) \simeq 0.06$ m.a.s. yr^{-1}, we get with the available data

$$H_0 \simeq 3.3\ 10^{-18}\ \text{s}^{-1} \simeq 100\ \text{km}^{-1}\ \text{s}^{-1}\ \text{Mpc}^{-1}.$$

We note that the apparent motion observed in 4C 34.47 is as expected if the two VLBI jets are perpendicular to the line of sight.

The main advantage of the method is that it does not depend on astronomical luminosity calibration scales. VLBI observations of a large sample of strong double radio sources with two-sided VLBI jets or with the largest angular sizes will fix the values of H_0 and q_0 in the near future. Conversely, once H_0 is obtained by this method, one may then try to solve some remaining problems of luminosity calibration.

4.6. Remarks concerning uncertainties

Assuming a uncertainty of about 0.01 m.a.s. yr^{-1} on the apparent motion corresponding to $z \simeq 0.5$, we obtain an uncertainty of about 15 percents on H_0. The value $H_0 \simeq 100$ km s^{-1} Mpc^{-1} is obtained supposing $q_0 = 1/2$. From (10), with $0 \leq q_0 \leq 1$, the additional uncertainty on H_0 is about 15%. So, with data used in Fig. 1, we finally have

$$H_0 \simeq 100 \pm 30\ \text{km s}^{-1}\ \text{Mpc}^{-1}.$$

Moreover, observations of two-sided VLBI jets will provide a good determination of H_0, even if the source is not exactly perpendicular to the line of sight. Let us call the jets coming toward and going foreward, the blue and red jets respectively. For sources with small redshifts, we have calculated the apparent velocities corresponding to beams with $\gamma_b = 10$, 5 and 3, i.e., $v \simeq 0.99\,c$, $0.98\,c$ and $0.94\,c$ respectively for $60° \leq \theta \leq 90°$ (Table 2).

The mean $\langle v \rangle = (|v_b| + |v_r|)/2$ of the absolute values of the apparent transverse velocities of the blue and the red jets is given in Table 3. As we can see except when $\theta = 60°$ and $\gamma \geq 5$, this mean is always equal to c within 6%. In practice, this happens as long as $|v_b|/|v_r| \leq 2$ and $\gamma \geq 3$, i.e., VLBI *observations of two-sided radio sources will provide a good determination of the cosmological*

Table 2. The apparent transverse velocities of two-sided VLBI jets

γ_b		10	5	3
$\theta=60$	v_b	$+1.70\ c$	$+1.66\ c$	$+1.54\ c$
$\theta=240$	v_r	$-0.57\ c$	$-0.57\ c$	$-0.55\ c$
$\theta=70$	v_b	$+1.41\ c$	$+1.39\ c$	$+1.30\ c$
$\theta=250$	v_r	$-0.69\ c$	$-0.69\ c$	$-0.67\ c$
$\theta=80$	v_b	$+1.18\ c$	$+1.16\ c$	$+1.11\ c$
$\theta=260$	v_r	$-0.83\ c$	$-0.82\ c$	$-0.80\ c$

Table 3. The mean of the absolute values of the apparent transverse velocities

γ_b	10	5	3
$\langle v_\perp \rangle$ $(\theta=90)$	0.99 c	0.98 c	0.94 c
$\langle v \rangle$ $(\theta=80)$	1.01 c	0.99 c	0.96 c
$\langle v \rangle$ $(\theta=70)$	1.05 c	1.04 c	0.99 c
$\langle v \rangle$ $(\theta=60)$	1.14 c	1.12 c	1.05 c

parameters, if the ratio of the apparent motions of the two jets is ≤ 2.

5. Conclusion

Superluminal sources in strong double radio sources with hot spots in extended lobes can be explained with a two-fluid model characterized by

i) a *non-relativistic jet* of $e^- - p$ plama, which carries most of the mass and kinetic power of the flow at a velocity $v_j \simeq 0.35\ c$. This thermal jet is responsible for the formation of hot spots in the extended lobes when it interacts with the external medium surrounding the radio source.

ii) a *relativistic beam* of $e^- - e^+$ plasma at a velocity $v_b \simeq c$. It moves in a channel through the non-relativistic jet.

iii) a magnetic field parallel to the jet and the beam which can stabilize the beam against Kelvin-Helmoltz instabilities and avoid a strong relaxation of the beam through Langmuir turbulence.

The interaction of the beam and the jet occurs at the surface of the channel and at the nose. The relativistic $e^- - e^+$ blobs moving in the channel produce the observed radio knots with apparent superluminal motions.

As long as the magnetic field in the jet is greater than a critical value B_c, the relativistic plasma can propagate in the jet, and when the magnetic field becomes smaller than B_c, the relativistic fluid dissipates via strong Langmuir turbulence which locally accelerates suprathermal particles (Pelletier et al., 1988; Sol et al., 1989).

Observations of two velocities in the VLBI jet of NGC 1275, and the limb brightening of the VLBI jet of M 87, give some support to the two fluid model even though these sources are not superluminal.

The main advantages of the two-fluid model is that it can explain superluminal radio sources with the relativistic fluid, and the formation of hot spots with the non-relativistic component.

The formation of the non-relativistic component can probably be explained by MHD extraction from the disk surrounding the black hole.

For strong double radio sources, the correlation of the relative strengths between VLBI jets and jets on large scales is a natural consequence of the presence of a larger fraction of relativistic e^- and e^+ in one beam. However, the kinetic energies of both jet and counter-jet are the same.

All strong double radio sources are expected to have relativistic ejections in VLBI jets even if the jets are perpendicular to the line of sight.

An important consequence related to the ejection of material with a velocity close that of light by nuclei of strong double radio sources is the possibility of determining the cosmological parameters q_0 and H_0 independently of any luminosity calibration. Indeed, when a source has jets perpendicular to the line of sight, measurement of the velocity of the ejecta, which is close to that of light, is a way to determine the fundamental parameters of the geometry of the Universe. Published data do not allow yet the determination of q_0. However, by adopting $q_0 = 1/2$, with existing data we find that the Hubble constant is $H_0 \simeq 100 \pm 30\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. Observation of a sample of strong double radio sources with two-sided VLBI jets or with the largest angular will fix H_0 in the near future.

Acknowledgements. We thank P. Charlot for providing us data concerning DA 193, D. Downes, P. Merat, J. Oort, M. Rees, H. Sol, J.F. Sygnet and P. Veron for useful comments and C. Douillet for typing out the manuscript. One of us (J.R.) thanks CNRS for financial support for this work.

References

Alef, W., Götz, M.M.A., Preuss, E., Kellermann, K.I.: 1987, *Astron. Astrophys.* **192**, 53

Barthel, P.D., Miley, G.K., Schilizzi, R.T., Preuss, E.: 1985, *Astron. Astrophys.* **151**, 131

Barthel, P.D., Hooimeyer, J.R., Schilizzi, R.T., Miley, G.K., Preuss, E.: 1989, *Astrophys. J.* **336**, 601

Blandford, R.D., Rees, M.J.: 1974, *Monthly Notices Roy. Astron. Soc.* **169**, 395

Blandford, R.D., Königl, A.: 1979, *Astrophys. J.* **232**, 34

Blandford, R.D., Payne, D.G.: 1982, *Monthly Notices Roy. Astron. Soc.*, **199**, 883

Browne, I.W.A., Clark, R.R., Moore, P.K., Muxlow, T.W.B., Wilkinson, P.N., Cohen, M.H., Porcas, R.W.: 1982, *Nature* **299**, 788

Browne, I.W.A.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 129

Charlot, P.: 1989, *Astron. Astrophys.* (in press)

Cohen, M.H.: 1986, *Highlights of Modern Astrophysics*, Wiley, New York, p. 299

Cohen, M.H., Barthel, P.D., Pearson, T.J., Zensus, J.A.: 1988, *Astrophys. J.* **329**, 1

Conway, J.: 1988, Ph.D. Thesis, University of Manchester

Draine, B.T.: 1983, *Astrophys. J.* **270**, 519

Ginzburg, V.L., Syrovatskii, S.I.: 1969, *Ann. Rev. Astron. Astrophys.* **7**, 375

Götz, M.M.A., Alef, W., Preuss, E., Kellermann, K.I.: 1987, *Astron. Astrophys.* **176**, 171

Hough, D.H., Readhead, A.C.S.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 114
Hough, D.H., Readhead, A.C.S: 1989, *Astrophys. J.* (in press)
Kellermann, K.I., Pauliny-Toth, I.I.K.: 1981, *Ann. Rev. Astron. Astrophys.* **19**, 373
Leahy, J.P., Muxlow, T.W.B., Stephens, P.W.: 1989, *Monthly Notices Roy. Astron. Soc.* **239**, 401
Lynden-Bell, D.: 1977, *Nature* **270**, 396
Maar, J.M., Backer, D.C., Wright, M.C.H., Readhead, A.C.S., Moore, R.: 1989, *Astrophys. J.* (in press)
Mestel, L.: 1961, *Monthly Notices Roy. Astron. Soc.* **122**, 473
Muxlow, T.W.B., Pelletier, G., Roland, J.: 1988, *Astron. Astrophys.* **206**, 237
Ozernoi, L.M., Sazanov, V.N.: 1969, *Astrophys. Space Sci.* **3**, 395
Pearson, T.J., Zensus, A.J.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 1
Pearson, T.J., Readhead, A.C.S., Barthel, P.D.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 94
Pearson, T.J., Readhead, A.C.S.: 1988, *Astrophys. J.* **238**, 114
Pelletier, G., Sol, H., Asseo, E.: 1988, *Phys. Rev. A* **38**, 2552
Phinney, E.S.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 301
Pudritz, R.E., Norman, C.A.: 1983, *Astrophys. J.* **274**, 677
Rees, M.J.: 1966, *Nature* **211**, 468
Rees, M.J.: 1967, *Monthly Notices Roy. Astron. Soc.* **135**, 345
Reid, M.J., Biretta, J.A., Junor, W., Muxlow, T.W.B., Spencer, R.E.: 1989, *Astrophys. J.* **336**, 112
Roland, J., Pelletier, G., Muxlow, T.W.B.: 1988, *Astron. Astrophys.* **207**, 16
Ryle, M., Longair, M.S.: 1967, *Monthly Notices Roy. Astron. Soc.* **136**, 123
Scheuer, P.A.G.: 1974, *Monthly Notices Roy. Astron. Soc.* **166**, 513
Scheuer, P.A.G., Readhead, A.C.S.: 1979, *Nature* **277**, 182
Schilizzi, R.T., de Bruyn, A.G.: 1983, *Nature* **303**, 26
Shaffer, D.B., Marsher, A.P.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 67
Shklovsky, I.S.: 1963, *Sov. Astron. AJ.* **7**, 748
Shklovsky, I.S.: 1965, *Sov. Astron. AJ.* **9**, 22
Shone, D.L., Porcas, R.W., Zensus, J.A.: 1985, *Nature* **314**, 603
Simon, R.S., Johnston, K.J., Eckart, A., Biermann, P., Schalinski, C., Witzel, A., Strom, R.G.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 155
Sol, H., Pelletier, G., Asseo, E.: 1989, *Monthly Notices Roy. Astron. Soc.* **237**, 411
Unwin, S.C.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 34
Ushida, Y., Shibata, K.: 1985, *Publ. Astron. Soc. Japan* **37**, 515
Walker, C.R., Benson, J.M., Unwin, S.C.: 1987, *Superluminal Radio Sources*, Cambridge University Press, Cambridge, p. 48
Walker, C.R., Walker, M.A., Benson, J.M.: 1988, *Astrophys. J.* **335**, 668
Wardle, J.F.C., Roberts, D.H.: 1988, IAU Symposium No. 129, *The impact of VLBI on Astrophysics and Geophysics*, Kluver, Dordrecht
Weinberg, S.: 1972, *Gravitation and Cosmology*, Wiley, New York, p. 485
Witzel, A., Schalinski, C.J., Johnston, K.J., Biermann, P.L., Krichbaum, T.P., Hummel, C.A., Eckart, A.: 1988, *Astron. Astrophys.* **206**, 245