Astron. Astrophys. 181, 14–18 (1987)

ASTRONOMY
AND
ASTROPHYSICS

Alternating side ejection or precession of jets in radio sources

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Received October 24, accepted December 31, 1986

Summary. The radio source 4CT74.17.1 has been put forward by Rudnick (1982) and also Rudnick and Edgar (1984) as an example of a radio source exhibiting the "preferential avoidance" effect, which they attribute to alternating side ejection. We show that the main features of the brightness distribution of this source can be modelled by a relativistic jet slowly precessing around an axis near the plane of the sky. This type of configuration may also explain the apparent one-sidedness of the jets in the sample of radio quasars of largest angular size studied by Wardle and Potash (1984).

Key words: radio sources: general – quasars: jets of – galaxies: jets of – relativity

1. Introduction

Many extragalactic radio sources consist of two more or less symmetrical lobes straddling a central component associated with the nucleus of an active galaxy or quasar. It is generally assumed that the central component indicates the position of a nuclear collimated energy source which energizes the outer radio blobs. The energetic link between central and outlying radio structures is sometimes observable in the form of jets. In most cases the jets are visible on one side of the central component only. This is usually explained as the result of relativistic beaming (Blandford and Königl, 1979; Scheuer and Readhead, 1979). In recent years the relativistic beaming hypothesis has gained much support from *VLBI* observations of the central components in strong radio sources. On the milliarcsec scale this component often shows a jet-like feature that points to the large scale (arcsec) jet suggesting that on the two scales the one-sidedness results from one and the same cause. There is much evidence in favour of relativistic motion on the milliarcsec scale (superluminal motion and radio variability, e.g. Cohen and Unwin, 1983). This suggests that also on the arcsec scale the one-sidedness is a result of relativistic beaming (cf. Scheuer, 1983). On the other hand the extended double structures (blobs) are expected to move through their ambient medium with velocities not much larger than a few tenths of the speed of light (Longair and Riley, 1979). The same holds for jets in head-tail sources, which generally are two-sided. There is no direct, conclusive proof for relativistic motion in one-sided arcsec-scale jets, and the possibility that these jets are non-relativistic and intrinsically one-sided cannot be discarded.

2. Jet precession instead of alternating-side ejection

There are two observational studies yielding results which seem to support the hypothesis that jets are ejected towards one side at a time. First, Rudnick and Edgar (1984) have pointed out that many double radio sources with central components show signs of what they call "preferential avoidance": maxima in the brightness distribution on one side of the central component do not correspond with radio emission at the same distances at the other side. The emission on one side seems complementary to the emission on the other side. The interpretation they favour is alternating side ejection. Second, Wardle and Potash (1984) selected the 8 radio sources with largest angular size from a sample of 32 4C QSRs with clearly resolved double or triple structure (Potash and Wardle 1979) for observation with the Very Large Array (VLA) and found one-sided jets in at least 6 of them. They argue that their subsample of 8 QSRs must comprise those nearest to the plane of the sky, which yields an upper limit to the amount of Doppler boosting and thus to the ratio of the flux densities in the jet and its counterpart. This upper limit is smaller than the lower limits they derive from their radio maps and they conclude that the one-sidedness of the jets cannot be entirely due to relativistic beaming.

In this paper we argue that these observations can be reconciled with the relativistic jet hypothesis if the ejection axis of the jets is slowly precessing. Such a precession of the central collimator (presumably a rotating massive black hole) has been invoked to explain the commonly found inversion symmetry (or S-symmetry) in radio sources (see Miley, 1980). Most likely the precession is caused by a second massive black hole in close orbit around the central hole in the nucleus of the galaxy (Begelman et al., 1980; Roos, 1987).

Precession of relativistic jets gives rise to a wealth of radio structures depending on velocity and orientation of the jet and on observational parameters such as dynamic range, noise level and resolution (Gower et al., 1982). Phenomenae which have been attributed to alternating side ejection are seen when the precession cone axis lies near the plane of the sky. If the observer's sensitivity is just high enough to see the jet when it actually is in the plane of the sky, it will become visible alternatingly at either side of the central source when a component of its movement is pointing towards the observer. As an example we show

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Send offprint requests to: E.J.A. Meurs below that this model can explain the brightness maxima and minima in the source 4CT74.17.1, which has been put forward by Rudnick (1982; see also Rudnick and Edgar, 1984) as a typical example of a source exhibiting alternating side ejection. Similarly for the largest radio sources studied by Wardle and Potash (1984), combining ejection near the plane of the sky with precession will increase the brightness of the jet coming out of the plane over that of its counterpart.

3. Source modelling

Our approach is essentially the same as in Gower et al. (1982). In our numerical simulation the jet is assumed to consist of a series of blobs ejected at equal time intervals, which move rectilinear with velocity $v_{jet} = \beta c$. They are allowed to disperse away from the jet axis at a speed of $0.1 v_{jet}$. Each blob is having the same constant emissivity. The brightness distribution is then fully determined by dispersion velocity, projection, Doppler boosting and precession parameters. We assume that the radio spectrum of the jet follows $S_\nu \propto \nu^{-\alpha}$. The Doppler boost factor is then

$$D = [\gamma(1 - \beta \cos \vartheta)]^{-(n+\alpha)} \tag{1}$$

where $n = 2$ for a continuous jet and $n = 3$ for each individual blob (Blandford and Königl, 1979). Other parameters in this expression are γ, the Lorentz factor $(1 - \beta^2)^{-1/2}$ and ϑ, the angle of the jet with the line of sight. The angle ϑ can be expressed in the angle i of the precession cone axis with the line of sight, the opening half angle ψ of the cone and a phase angle φ:

$$\cos \vartheta = \cos i \cos \psi + \sin i \sin \psi \cos \varphi \,. \tag{2}$$

The phase φ describes the direction of blob ejection on the cone surface and increases linearly in time for a constant precession period; $\varphi = 0°$ away from the observer. The precession cone axis is assumed to lie in the plane of the sky, $i = 90°$, and therefore the ratio of jet/counterjet brightness is given by

$$S_{\rm jet}/S_{\rm cjet} = \left[\frac{1 - \beta \sin \psi \cos \varphi}{1 + \beta \sin \psi \cos \varphi}\right]^{-(n+\alpha)} . \tag{3}$$

From this formula we see that the precession introduces brightness variations on both sides of the nucleus which are complementary to each other. The angle ψ determines the curvature observed in the plane of the sky, β the maximum Doppler boost factor, φ the distance of the first maximum to the central component and thereby the armlength ratio.

4. 4CT74.17.1

The source 4CT74.17.1 was observed at 49, 21 and 6 cm with the Westerbork telescope (WSRT) by van Breughel and Willis (1981). The 6 cm map served as a typical example of alternating side ejection in Rudnick (1982), while the 21 cm map was shown as one of the illustrations of this phenomenon in Rudnick and Edgar (1984). The 6 cm map shows a one-sided jet extending from a central component and an outer radio lobe at the other side of the central component (to the SE). On the 21 cm map there is also an outer lobe beyond the end of the jet (to the NW), further away from the central component than the opposite lobe. The WSRT 21 cm map of 4CT74.17.1 is reproduced in our Fig. 1a. Both the 6 cm and the 21 cm map illustrate the alternating-side phenomenon when the maps are overlaid by a copy of themselves which either is rotated by 180° around the central component or is a mirror image: regions of radio emission are seen to coincide with regions without emission.

Modelling the 21 cm brightness distribution of 4CT74.17.1 as described above, the precession cone axis is assumed to lie in the plane of the sky ($i = 90°$). A reasonable value for the opening half angle of the cone can be estimated from the jet curvature observed on the WSRT 6 cm map ($\psi = 10°$). The radio source is assumed to have a steep radio spectrum ($\alpha = 1$). The redshift of this radio galaxy ($z = 0.107$) is used to convert the calculated source structure to angular size in order to compare our result with the published 21 cm map; the Hubble constant is taken as $100\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

In Fig. 1b we show one of our models which reproduces the essential features of the observed brightness distribution for a relativistic jet with $\beta = 0.95$, a precession period of $9\,10^5$ yr and a present ejection phase angle of $\varphi_0 = 135°$. A precession time of this order of magnitude is also found for other radio sources for which precession models have been made, and is consistent with the precession times expected from massive binary black hole models (Roos, 1987). The density of dots is proportional to the flux density in the model. The main features in this figure are a bright jet to one side of the centre and outlying brightness enhancements at either side corresponding to the outer lobes. Position and curvature of the jet are similar to observed in the 6 cm and 21 cm maps. Both lobe positions agree with the outer high brightness regions in the radio maps, the one beyond the end of the jet at greater distance from the centre and more diffuse than the lobe at the opposite side. All these features are in accordance with the WSRT 21 cm results. In addition there are low brightness features connecting NW-lobe and jet-end at one side and SE-lobe and centre at the other. These fainter regions are produced in this model at places where, due to the precession, the jet has a velocity component away from the observer. They may disappear at higher noise levels as is illustrated in Fig. 1c, where only a one-sided jet and two outlying lobes are seen. The relative brightness level of the jet along the major axis of the model is given in Fig. 1d. This simple type of model already produces the essential characteristics of the observed source, which are considered to be the presence of a jet emerging from the central component, the curvature of the jet and the relative positions of the lobes. Other effects, like ram pressure and density gradients in the surrounding medium, may become increasingly influential at larger distances from the centre. These effects will have to be taken additionally into account, in order to achieve a detailed correspondence of model calculation and observed source structure in between the jet and the lobes. Other effects (like the surrounding medium) may become increasingly influential at larger distances from the centre.

At this stage it is of interest to have a closer look at the level of preferential avoidance displayed in the radio maps of 4CT74.17.1 and at the way they served as examples of alternating-side ejection. The 6 cm map, first presented in overlay with its inverse by Rudnick (1982), shows a feature at about the 5σ-level opposite to the jet, halfway between centre and SE-lobe where no radio emission should be present (Fig. 4 in van Breugel and Willis, 1981). At the very same position there is a noticeable brightness enhancement in the 21 cm map of van Breugel and Willis (their Fig. 2), indicating this to be a real feature. Even more, this 21 cm contour map and also the corresponding

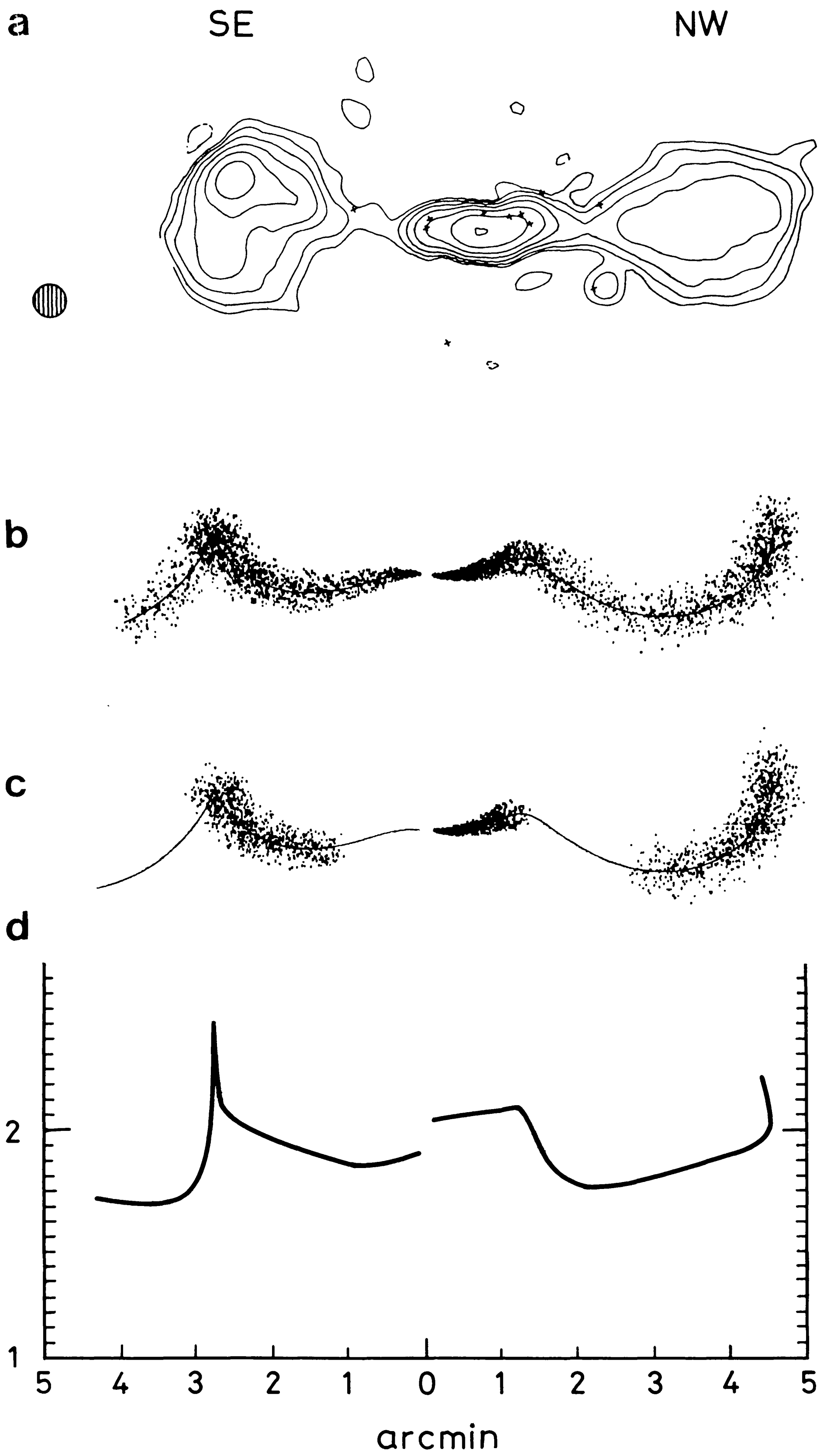

Fig. 1a–d. The brightness distribution observed for the radio source 4CT74.17.1 and expected for a simple model with precessing relativistic jets. **a** WSRT 21 cm contour map; **b** calculated from model, as described in text; **c** idem, but with a threshold applied to the lowest brightness levels in order to account for the signal-to-noise level of the observation; **d** logarithm of relative brightness of the jet along the major axis of the model, in arbitrary units. The model calculation is aimed at reproducing the essential characteristics of the source, which are a jet emerging from the centre and two outer brightness enhancements. Radio emission from the central component itself is not included.

radiophoto (Fig. 3 in van Breugel and Willis) clearly show low-brightness regions connecting jet-end with NW-lobe and central source with SE-lobe. Although well above the noise level, the lower contour levels which outline particularly these connecting bridges, were dashed by Rudnick and Edgar (1984) when overlaying the 21 cm map with its reverse, apparently to produce a stronger case of preferential avoidance. This was achieved by dashing contours in an inconsistent way, however: the two lowest contours around the SE-lobe, but the three lowest around the NW-lobe; the lowest contours of the jet were kept fully drawn. Further examination of their illustration shows that unlike other examples they present, the overlay was not just flipped 180° around the nucleus but was also shifted over almost half a beam, resulting in the avoidance at jet-end/inner side of SE-lobe (which is the more prominent one due to their dashing) standing out a bit clearer in their illustration.

Altogether 4CT74.17.1 does not appear supporting the alternating side ejection hypothesis very convincingly. Instead, the overall brightness distribution of this source is consistent with being produced by a precessing two-sided relativistic jet. Both two-sided jets and precession have been observed in radio sources and offer a much more natural explanation for sources suspected of ejecting alternatingly. Possibly 4CT74.17.1 is a fortuitous case for which signal-to-noise level and brightness changes over the source combine to place it between sources clearly recognized as having two-sided jets and sources thought to exhibit preferential avoidance, thus revealing the real nature of the latter phenomenon.

5. One-sidedness in the largest QSRs

A small amount of inversion symmetric curvature is quite common in radio sources. Curvature over more than 10° is present in at least 5 of the 8 largest sources in the sample of 32 4C QSRs selected by Wardle and Potash (1984). A comparable amount of bending out of the plane of the sky must also have occurred. Therefore the extended double structure may well be within $0 < \cos i < 8/32$ while a considerable part of one of the jets has a smaller angle with the line of sight. Bending over about 10° could easily let disappear the counterjet below the noise in their maps.

Wardle and Potash (1984) actually present radio maps for 6 of their 8 sources; one more map is found in Potash and Wardle (1979). The sources are triples with, at one side of the source, jets or jet-like structures in between central component and outer lobe. Although there is no information on the noise level in the Wardle and Potash maps, there are in 3 cases noisy features between central component and outer lobe at the side opposite to the jet. The morphology of these features is suggestive of a lower brightness counterjet that starts appearing out of the noise. Interestingly, in two of those cases the S-symmetry seen for most of the other sources is not apparent, meaning that the brightness ratios $S_{\rm jet}/S_{\rm cjet}$ may be rather modest indeed. The distances between outer lobes and central component are, for both these sources, greater at the side where the jet is seen, as might be expected if the small difference observed between $S_{\rm jet}$ and $S_{\rm cjet}$ originated here from Doppler boosting by the source axes lying slightly out of the plane of the sky. The third case has the one but highest lower limit on $S_{\rm jet}/S_{\rm cjet}$ as given by Wardle and Potash but has also pronounced S-symmetry as would be consistent with increased Doppler boosting due to jet precession. The other sources exhibit mainly one-sided jets on the maps presented, and do show the inversion symmetric curvature as expected for precessing jets. Most of the largest QSRs may therefore have larger Doppler boostings than would follow from their assumed orientation near the plane of the sky.

The lower limits on $S_{\rm jet}/S_{\rm cjet}$ that Wardle and Potash (1984) list for the 8 QSRs are well accounted for when in addition to the overall source orientation, precession of the radio jet is considered. Following Wardle and Potash, the sources are assumed to be uniformly distributed over $0 < \cos i < 8/32$, that is between $i = 90°$ and $i = 75\overset{\circ}{.}5$ with a median $i = 82\overset{\circ}{.}8$. Without precession, the adopted Doppler boosting results in $S_{\rm jet}/S_{\rm cjet} = ((1 + \beta \cos i)/(1 - \beta \cos i))^{2+\alpha}$ which they evaluate for $\beta = 1$ and radio spectral index $\alpha = 0.75$. The median and minimum angles with the line of sight then correspond to maximum brightness ratios of 2.0 and 4.1, respectively. Precession results in minimum angles i smaller by typically 10° and therefore maximum values for $S_{\rm jet}/S_{\rm cjet}$ of 5.4 and 11.3, respectively. It is important to note that if jet precession commonly occurs among these radio sources, even the ones nearest the plane of the sky will always have appreciable brightness ratios between both jet sides, of order of 3 and larger. Such values easily account for all but two of the $S_{\rm jet}/S_{\rm cjet}$ lower limits listed by Wardle and Potash. The two remaining cases (with exceptionally high lower limits) do not offer a serious problem if reasonable greater ranges are allowed for factors that let increase the ratio $S_{\rm jet}/S_{\rm cjet}$, for instance orientations slightly further out of the plane of the sky for individual cases. Indeed the observed variation in intrinsic linear source size is too large to be consistent with the basic Wardle and Potash assumption of one size uniformly distributed over a narrow inclination range near the plane of the sky.

It is interesting to note that a similar amount of precession as appropriate to the largest QSRs is required to explain the bending observed in core-dominated, flat-spectrum sources (Moore et al., 1981), as well as the size of the extended structures around superluminal (core-dominated) sources (Schilizzi and de Bruyn, 1983), as double radio sources seen edge-on.

6. Conclusion

The source modelling of 4CT74.17.1 and the discussion of the largest QSRs have shown that at low brightness levels there is evidence for two-sided jet morphology with brightness variations induced by periodic Doppler effects. Obviously, any emission at both sides of a central component invalidates hypotheses in which radio jets are supposed to eject to one side only at any instant. We therefore conclude that (slow) precession of relativistic jets provides an attractive explanation for both the preferential avoidance effect noted by Rudnick and Edgar and the apparent one-sidedness of jets found by Wardle and Potash for the largest angular size QSRs. We predict that observations with higher signal-to-noise ratios are likely to reveal counterjets in the latter sources.

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