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Research Note

A compact radio component in 4C 41.17 at z=3.8: a massive clump in a forming galaxy?

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Abstract. We present the results of a study of the centiarcsecond radio structure at wavelength of 18 cm in the high-redshift galaxy associated with the radio source 4C 41.17 (z = 3.8). We have detected a component of size not more than 15 mas ($\simeq$ 65 pc, H_o = 75 km s^{-1} Mpc^{-1}, q_o = 0.5) at a distance of $\simeq$ 2.9 kpc from the nucleus of the galaxy which accounts for $\sim$ 30% of the flux density of the previously known unresolved VLA component. We speculate that the radio component is associated with a clump in the interstellar medium. The estimate of its mass, $1.5 \times 10^8 M_{\odot}$, is consistent with those of subgalactic structures preceding formation of globular clusters in the early stages of the evolution of galaxies.

Key words: galaxies: individual: 4C 41.17 – radio continuum: galaxies – galaxies: jets – galaxies: star clusters

1. Introduction

Galaxies associated with powerful radio sources were more than a thousand times more common at $z \sim 2$ than at the present time, and must have played a fundamental role in the formation and evolution of galaxies in general. Radio galaxies are the only objects at redshifts $z > 2$ which, as a class, can be well resolved with optical telescopes. In many cases a radio structure of distant radio galaxies contains compact features unresolved on the arcsecond scale. In order to investigate the nature of compact features and their possible role in the alignment effect we have begun a programme to study the most distant radio galaxies with VLBI.

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Table 1. VLBI telescopes and their characteristics at λ = 18 cm

Radio telescope	Diameter (m)	$T_{\rm sys}$ (Jy)	Sensitivity (K/Jy)
Effelsberg	100	25	1.07
Jodrell Bank	76	80	0.95
Noto	32	600	0.10
Onsala	26	324	0.09
Westerbork[a]	56	138	0.48

[a] The Westerbork telescope was used in phased array mode with 5 antennas; an equivalent diameter is given.

A particularly suitable candidate for such a study is the radio galaxy 4C 41.17 (0647+415) at z = 3.8 (Chambers et al. 1988). This is the third most distant galaxy known to date. *HST* studies by van Breugel (1996) have shown that it is highly clumped on sub-kpc scales. VLA maps of 4C 41.17 show unresolved components on the scale of $<$ 400 mas (Chambers et al. 1990, Carilli et al. 1994).

2. Observations, calibration and data reduction

The observations took place on May 28–29, 1993 with the European VLBI Network (EVN). Data from five telescopes were used for imaging: Effelsberg (Germany), Jodrell Bank (UK), Noto (Italy), Onsala (Sweden), and Westerbork (The Netherlands). The data were recorded on MkIIIA terminals with a total bandwidth of 56 MHz (mode A, Alef 1989) at all telescopes except Noto where a VLBA recording terminal was used with a total recorded bandwidth of 32 MHz. The telescopes and relevant sensitivities are listed in Table 1.

4C 41.17 was tracked for approximately 10 hours. Three scans (approximately 75 minutes in total) distributed over the observing session were dedicated to observing a strong fringe finder and calibrator 4C51.37 (1739+522) and two scans (26 minutes in total) to the flux density calibrator DA193 (0552+398). The data were correlated at the MPIfR in Bonn with the phase centre at RA = $06^h47^m20\overset{s}{.}527$ and DEC = $41°34'03\overset{''}{.}60$ (epoch 1950.0).

Fringe fitting and phase calibration of the data were carried out using the NRAO AIPS package (Cotton 1995), and amplitude calibration using *a-priori* flux density values and $T_{\rm sys}$ measurements was made using the Caltech VLBI Package (Pearson 1991). The NRAO AIPS package was used for self-calibrating and imaging (Walker 1995a).

The off-source noise in the image obtained with natural weighting of uv-data is about 80 μJy/beam compared with a predicted "theoretical" noise of about 60 μJy/beam (Walker 1995b). The discrepancy of a factor of ~ 1.3 is to be attributed to losses in sensitivity due to the non-ideal performance of various parts of observing and data handling instrumentation and a possible increase of the system temperature at some telescopes due to radio interference. The Noto radio telescope was particularly affected by the latter.

3. Results and discussion

The VLA map of the source, reproduced in Fig. 1a from Carilli et al. (1994), represents the inner few kiloparsecs of the galaxy. Our VLBI map (Fig. 1b) has been formed with the phase centre at the position of the component B1 in Fig. 1a. This image has been restored with natural weighting, which provides the lowest noise per pixel at the expense of angular resolution (Walker 1995b). The main feature in our VLBI image has a flux density of $\simeq 9$ mJy (about 30% of the flux density in B1, previously estimated by Chambers et al. 1990 and Carilli et al. 1994). The AIPS task IMFIT applied for the image restored with uniform weighting (which provides the higher angular resolution but has the higher noise, Walker 1995b) gives the upper limit of deconvolved angular size of the feature of $\simeq 15$ mas. It corresponds to the linear size of $\simeq 65$ pc at $z = 3.8$. (H_o = 75 km s^{-1} Mpc^{-1}, q_o = 0.5).

The weak extended feature to the south-west at the angular separation of $\simeq 100$ mas from the main component accounts for $\simeq 240\,\mu$Jy and its peak brightness of $\simeq 3.2\sigma$ of the field noise is near the detection limit of our experiment. Its position angle relative to the strongest VLBI feature detected is PA$\simeq -115°$, an intermediate value between the direction from N to B1 (PA = $-103°$) and from B1 to A (PA = $-126°$, Fig. 1a). While this component is too weak to play a serious rôle in the overall flux density budget of B1, its position might be indicative of the path of jet propagation. No other components exceeding 3σ-level have been detected within the field of view of $0\overset{''}{.}6$. The latter is limited by bandwidth smearing and corresponds to a 10% drop in the response to a point source (Wrobel 1995).

Since the nucleus of the source is assumed to be associated with the flat spectrum VLA feature N (Carilli et al. 1994), one can conclude that any jet connecting N, B1, and A must bend from PA = $-103°$ to PA = $-126°$ and this bending must occur somewhere in the vicinity of the component B1. The intermediate value of the position angle of the weak VLBI feature supports this assumption. One can assume that the jet bends on the scale comparable to the distance from the brightest component to the extended weak component (Fig. 1b), $\simeq 100$ mas. Under this assumption, the length of the bent segment of the jet is $l_B \simeq 860$ pc.

Using the usual assumptions (Miley 1980), we estimate the "minimum energy" magnetic field in the VLBI radio component as $B_{\rm me} \simeq 1.5 \times 10^{-2}$ Gauss , the minimum energy density $u_{\rm me} \simeq 2 \times 10^{-5}$ erg cm^{-3} , and its total energy $E_{\rm VLBI} \simeq 10^{56}$ erg. Given that the observed total radio luminosity of the VLBI component is $L_{\rm R} \simeq 0.7 \times 10^{45}$ erg s^{-1}, the radiative lifetime of the component is $\tau \simeq 2.2 \times 10^3$ yr. We note that these estimates correspond to the upper limit of the compact component's size.

Assuming that a jet from the component N (nucleus) "feeds" the compact feature B1 and that the actual size of the main VLBI feature is comparable with the upper limit obtained, one can estimate the jet's bulk kinetic power $L_{\rm J} = \epsilon L_{\rm R}$, where $\epsilon \lesssim 0.1$ is the conversion efficiency of bulk kinetic energy to synchrotron radiation (e.g. Begelman et al. 1984). We assume the bulk velocity of the jet $v_{\rm J} = c$, because this minimizes the momentum flux for a given jet kinetic energy (e.g. Bridle and Perley 1984). The overall morphology of the source suggests that, after interaction with the component B1, the jet propagates toward component A and serves as its major power supply (Fig. 1a). We therefore consider that the jet has the same bulk velocity before and after interaction with component B1, but is bent by an angle of $\Delta_{\rm PA} \simeq 12°$ near the bright compact feature. The corresponding rate of momentum transfer to the compact component is given by $\dot{m} = L_{\rm J}/v_{\rm J} = L_{\rm R}/\epsilon c$. Assuming the momentum exchange takes place in the region where the jet is bent which we estimated earlier as $l_{\rm B} \simeq 860$ pc, and assuming the momentum accumulated by the matter associated with the compact feature during its radiative lifetime τ does not cause this feature to be displaced by more than its size, $l_{\rm B}$, momentum conservation requires the mass associated with the compact feature in B1 to be $M_{\rm B} \gtrsim 1.5 \times 10^8 M_\odot$. We note that the estimate above is based only on the information on the relative position of the strong and weak components in our VLBI map, and does not depend on the flux density of the latter.

We also note that this mass estimate is based on the assumption that the jet is close to the plane of the sky. This assumption seems to be realistic in the case of 4C 41.17 since the source nucleus, component N, is not obviously Doppler boosted which would require jet ejection close to the line of sight. Similar estimates of the mass required for bending a radio jet have been obtained by Barthel and Lonsdale (1983), Lonsdale and Barthel (1986a,b) for quasars 4C 04.81, 4C 29.50, 3C 205 and 3C 268.4. Our case differs from these in that 4C 41.17 is a galaxy with an extended optical structure, in which future deeper optical studies may well be able to trace the massive ISM clump.

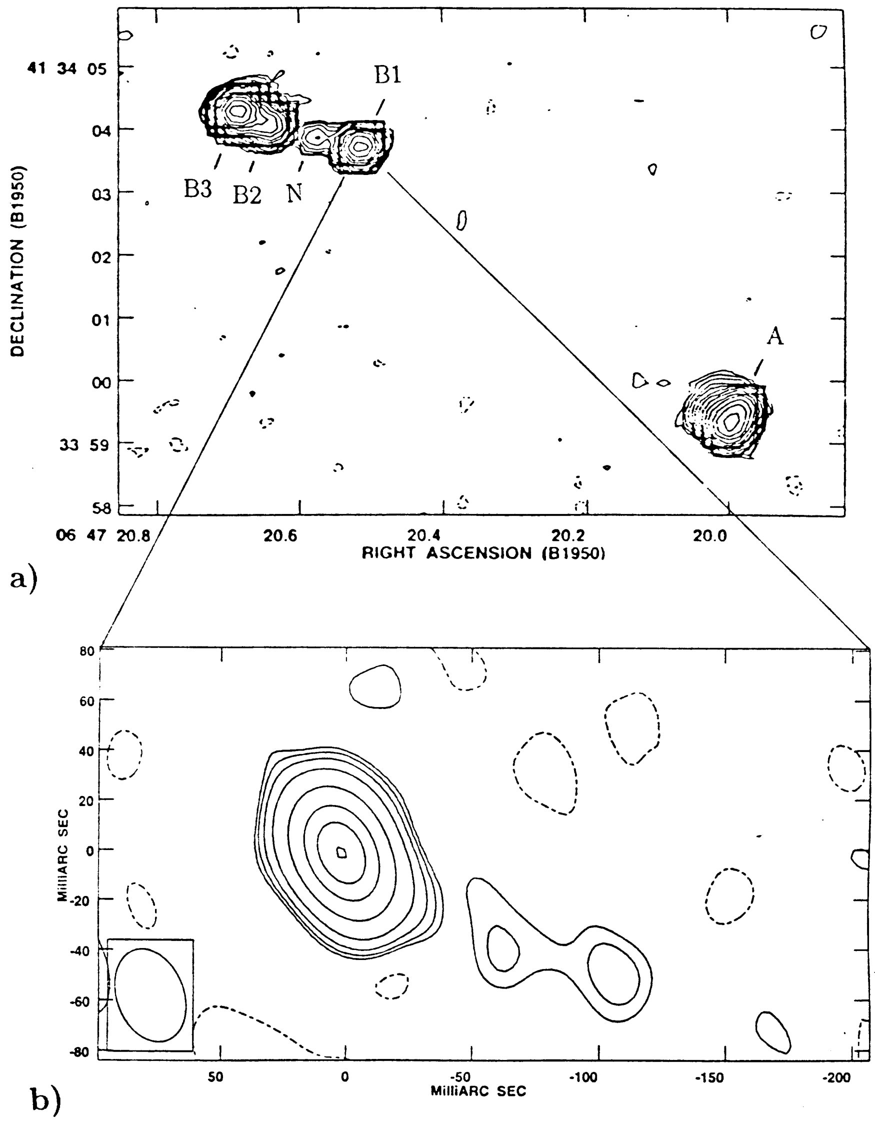

Fig. 1. a VLA image of 4C 41.17 at 6 cm with a resolution of 0.″4 (Carilli et al., 1994). Contour levels: $-0.5, 0.5, 1, 2.5, 5, 10, 25, 50, 75, 99\%$ of the peak brightness of 15.3 mJy/beam. **b** VLBI 18 cm imge of the component B1 obtained with natural weighting. Contour levels: $-2, 2, 3, 5, 10, 25, 50, 75, 99\%$ of the peak brightness of 8.2 mJy/beam; restoring beam is 38.1×26.8 mas in PA 21.°4.

The mass associated with the compact radio feature in B1 is typical for "pre-disrupted" clumps which evolve into globular clusters (Fall and Rees, 1977). It has been shown by Rees (1977) that tidal shocking erases all galactic substructures with masses larger than a typical globular cluster mass of $\sim 10^4 - 10^6\, M_\odot$. It is therefore possible that the clump we see in 4C 41.17 is a short-lived phase preceding the formation of a globular cluster.

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References

Alef W. 1989, in Very Long Baseline Interferometry, eds. M.Felli and R.Spencer, Kluwer, Dordrecht, p. 97
Barthel P.D., Lonsdale C.J., 1983, MNRAS 205, 395
Begelman M.C., Blandford R.D., Rees M.J., 1984, Rev. Mod. Phys. 56, 255
Bridle A.H., Perley R.A., 1984, ARA&A 22, 319
Carilli C.L., Owen F.N., Harris D.E., 1994, AJ 107, 480
Chambers K.C., Miley G.K., Joyce R.R., 1988, ApJ 329, L75
Chambers K.C., Miley G.K., van Breugel W., 1990, ApJ 363, 21
Cotton W.D., 1995, in Very Long Baseline Interferometry and the VLBA, eds. J.A.Zensus, P.J.Diamond, P.J.Napier, ASP Conf. Series, p. 189
Fall S.M., Rees M.J., 1977, MNRAS 181, 37P
Lonsdale C.J., Barthel P.D., 1986a, ApJ 303, 617
Lonsdale C.J., Barthel P.D., 1986b, AJ 92, 12
Miley G.K., 1980, ARA&A 18, 165
Pearson T.J., 1991, BAAS 23, 991
Rees M.J., 1977, in Evolution of galaxies and stellar populations, eds. B.M.Tinsley and R.B.Larson, Yale University Press, p. 339

van Breugel W., 1996, in Extragalactic Radio Sources, Proceedings of the IAU Symposium No. 175, ed. C.Fanti, Kluwer Acad. Press, in press

Walker R.C., 1995a, in in Very Long Baseline Interferometry and the VLBA, eds. J.A.Zensus, P.J.Diamond, P.J.Napier, ASP Conf. Series, p. 247

Walker R.C., 1995b, in in Very Long Baseline Interferometry and the VLBA, eds. J.A.Zensus, P.J.Diamond, P.J.Napier, ASP Conf. Series, p. 133

Wrobel J.M, 1995, in Very Long Baseline Interferometry and the VLBA, eds. J.A.Zensus, P.J.Diamond, P.J.Napier, ASP Conf. Series, 411

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