What bent the jets in 4C 34.16?

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ABSTRACT

The steep-spectrum radio source 4C 34.16 lies in a poor cluster of galaxies and is symmetrically bent in a wide C-shape. In order to investigate the origins of its bent shape, we have obtained X-ray, optical and radio observations of this object and its environment. Our ROSAT PSPC observation reveals the existence of substantial substructure in the intracluster gas similar to the features seen in simulations of cluster mergers. The most striking of these features is a 'wake' of X-ray emission between the radio lobes. Our data and analysis provide strong evidence that the existence of this wake is related to the mechanism responsible for the bending of the jets. Both of these phenomena can be explained by a minor merger event, in which a small infalling galaxy group or a lump of cool primordial gas has disturbed the cluster. A simple hydrodynamical description of the shape of the radio jets, which incorporates both ram pressure and buoyancy forces, places constraints on the galaxy velocity relative to the intracluster gas; we find that a galaxy velocity of $\sim 300$ km s$^{-1}$ can account for the bending of the jets as well as explaining the density enhancement in the wake.

Key words: galaxies: clusters: general – galaxies: individual: 4C 34.16 – intergalactic medium – galaxies: jets – radio continuum: galaxies – X-rays: galaxies.

1 INTRODUCTION

Wide-angle tailed radio galaxies (WATs) are extended double radio sources which appear bent in a wide 'C' shape. Their structure, as it is seen in radio maps, gives the impression that the jets are being 'swept back' by the dynamic pressure resulting from the motion of the associated galaxy through the surrounding intergalactic medium. This ram pressure model was first developed by Begelman, Rees & Blandford (1979), and has been studied in more detail by Vallée, Bridle & Wilson (1981) and Baan & McKee (1985). Unfortunately, this model failed to provide a satisfactory explanation for the observed features of previously studied WATs (e.g. Eilek et al. 1984). The reason for this failure is that WATs are usually associated with D and cD galaxies in clusters, and such galaxies are believed to reside at the gravitational centres of clusters (Merritt 1984), and are not expected to have the large speeds relative to the intracluster medium (ICM) assumed to be necessary for the ram pressure model. The expectation that D and cD galaxies are located at the minimum of the cluster gravitational well has been confirmed by measurements of velocities of D and cD galaxies in clusters (Quintana & Lawrie 1982; Bird 1994), and by the coincidence between the location of dominant galaxies and the centres of their host clusters inferred from X-ray observations (Jones & Forman 1984). Recently, it has been suggested that the necessary ram pressure may be provided during cluster mergers (e.g. Pinkney, Burns & Hill 1994). X-ray observations show convincing evidence that clusters merge frequently (Edge et al. 1990; Gioia et al. 1990; Henry et al. 1992), and numerical simulations (Roettiger, Burns & Loken 1993; Schindler & Müller 1993) indicate that large gas motions persist in the clusters for a long time after the merger event.

Buoyancy forces will also contribute to the bending of the radio jets. If the jets are less dense than their surroundings, buoyancy forces drag them towards regions in the ICM where the densities are equal. This buoyancy model, which was first proposed by Gull & Northover (1973) in connection with strong double radio sources such as Cygnus A and was recalled by Cowie & McKee (1975) as a possible bending mechanism for tailed radio sources, has been recently applied by Worrall, Birkinshaw & Cameron (1995) to explain successfully the shape of the jets in the dumbbell radio galaxy NGC 326.

In fact, of course, both buoyancy and ram pressure must act on the jets to give them their observed shape. The degree to which each force is involved is set by the physical...
parameters of each particular case, and depends on the density distribution of the ICM, the position and the velocity of the host galaxy, and the density and velocity of the jets. Thus, having detailed information on the density distribution of the ICM from X-ray observations, and invoking ram pressure and buoyancy forces to describe the shape of the jets, WAT sources can provide useful diagnostics of jet properties.

In order to exploit these diagnostic properties and to look for evidence of the merger activity necessary to produce significant ram pressure effects, we obtained X-ray, optical and radio observations of the nearby (z = 0.078; Gregory & Burns 1982) WAT source 4C 34.16, which is located in a Zwicky cluster (Z 0357.9 + 3432) of richness class 0–1 (Burns, Gregory & Holman 1981). This radio source has a very symmetric structure, which suggests that the bending of its jets might be explained by a simple dynamical model. Additionally, it has a steep low-frequency radio spectrum, with a spectral index of α > 1.2 (F ∝ ν−α) in the frequency range from 38 to 178 MHz (Baldwin & Scott 1973). Such steep spectra arise when jets are confined against adiabatic dissipation for so long that radiative losses steepen the spectrum right down to low frequencies. This confinement is almost certainly provided by the ICM of a surrounding cluster of galaxies.

Previous X-ray observation performed with the Einstein IPC (Burns et al. 1981) revealed that 4C 34.16 is indeed surrounded by the ICM of a poor cluster of galaxies. Although the poor spatial resolution of the IPC (FWHM ~ 1.5 arcmin) did not reveal the fine structure of the gas, the Einstein image gives the first hint that the ICM of this cluster is perturbed, and that it is worthy of more detailed examination. Additionally, Z 0357.9 + 3432, being a poor cluster, is a good candidate for revealing details of any interactions, since the energy density stored in such an ICM is relatively low, and so its response to the impact from the jets will be much more apparent than in richer systems. Further, this response is more readily detectable in poor systems, because any X-ray perturbations in larger clusters will be diluted by the long column of non-interacting hot gas through which the interaction is observed.

In Section 2 we present a VLA radio continuum map of 4C 34.16, and in Section 3 we briefly explore the optical properties of its environment. Our ROSAT X-ray observations reveal that 4C 34.16 is, indeed, surrounded by the ICM of a poor cluster, and we use these observations to quantify the density distribution and temperature of the ICM (Section 4). The X-ray data also reveal evidence for a recent merger in this cluster in the form of a wake behind the galaxy and a ring at large radii in the X-ray emission. By adopting a simple dynamical model, we can explain both the bending of the radio jets (Section 5) and the properties of the wake (Section 6) if the merger caused 4C 34.16 to move at ~ 300 km s⁻¹ relative to the ICM.

2 RADIO OBSERVATIONS

4C 34.16 was observed with the Very Large Array (VLA) as part of a programme to study radio sources with steep low-frequency spectra. The first observations were made at 20 cm in 1982 April with the VLA in the A configuration providing a resolution of 1.4 arcsec. The observations were made in snapshot mode consisting of three snapshots of 5-min duration, each separated by about 80 min, thereby providing reasonable uv coverage for the detection of extended structure on a scale up to ~ 40 arcsec. The data were analysed and cleaned in the normal way, giving a map with rms noise level of ~ 1 mJy beam⁻¹. These observations revealed a point source of flux density 4 mJy at RA = 04° 00' 54.86, Dec. = +34° 43' 09.93 (J2000), coincident with the nucleus of the D-type galaxy in the optical data. The map also revealed evidence of poorly mapped structure on a scale larger than 40 arcsec, which was substantially resolved out. Further observations were therefore made in 1983 January with the VLA in C configuration, giving a resolution of ~ 13 arcsec providing sensitivity to emission on scales up to ~ 6 arcmin. A similar snapshot observing strategy was employed, producing data with a similar noise level of ~ 1 mJy beam⁻¹. The resultant cleaned map is shown as contours overlaid upon the ROSAT X-ray grey-scale map in Fig. 1, revealing a classic WAT morphology. The total flux density in the northern lobe is 590 mJy, and in the southern lobe it is 535 mJy. Our radio map has a better signal-to-noise ratio than previous radio observations of the same cluster (Burns & Owen 1979; Gregory & Burns 1982).

3 OPTICAL OBSERVATIONS

The field containing 4C 34.16 was observed using the Fred Lawrence Whipple Observatory 48-inch telescope on Mount Hopkins, Arizona. A 15-min exposure was obtained through an I-band filter. The observations were made through cirrus, and so the data are non-photometric; the seeing was moderate (~1.5 arcsec). The image was recorded on a 2048 × 2048 Tektronix CCD, which resulted in a scale of 0.33 arcsec pixel⁻¹. The data were flat-fielded and rotated to place north at the top; the resulting image is reproduced in Fig. 2, overlaid by a contour plot of the X-ray image.

The relatively low galactic latitude of this field (b = −14°) explains the high density of stars, but analysis of the sizes of the objects in the field reveals very few extended objects (i.e., galaxies). There is little evidence for any enhancement in the density of galaxies in the vicinity of 4C 34.16, confirming the status of this system as a very poor cluster.

The non-photometric conditions mean that we cannot use these data to provide absolute photometry of the host galaxy. We can, however, use them to quantify any morphological disturbances in this system. In fact, isophote-fitting to these data reveals that the host galaxy is an undisturbed elliptical galaxy. Its major-axis light profile is well described by a de Vaucouleurs law with an effective radius of \( R_e = 13 \pm 1 \) arcsec = 30 ± 2 kpc. Such a value is typical of the effective radii of the brightest galaxies in poor clusters (e.g. Morbey & Morris 1983).

## References

1. The source observed by Fantin et al. (1987) with the VLA at 1.4 GHz is not 4C 34.16 but 4C 36.14.
2. Here, as throughout this paper, we have adopted a Hubble constant of \( H_0 = 50 \) km s⁻¹ Mpc⁻¹, which places the system at a distance of 470 Mpc.

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4 X-RAY OBSERVATIONS

The field that contains 4C 34.16 was observed using the Position Sensitive Proportional Counter (PSPC) on the ROSAT satellite in 1993 September for 22,792 s. The PSPC operates in the energy range 0.1-2.5 keV; it produces images with a spatial resolution of $\sim 25$ arcsec FWHM with moderate energy resolution (Briel et al. 1996, in preparation). Extended X-ray emission was detected around the radio source, as expected for the ICM of a poor cluster. The cluster emission is completely contained within the central $\sim 0.73$ circular aperture bounded by the PSPC rib-support structure. The source is therefore only mildly affected by the energy-dependent vignetting function of the X-ray telescope. A grey-scale image of the X-ray emission from the cluster covering the full (0.1–2.5 keV) energy range of the PSPC is presented in Fig. 1, overlaid by our radio map at 20 cm.

4.1 Spatial analysis

4.1.1 Overall gas distribution

Spatial analysis of the PSPC data was performed using the IRAF PROS 'XSPATIAL' package. In order to obtain the general characteristics of the ICM of the cluster (i.e., its central density and temperature) and to compare them with previous findings of similar systems, we performed the traditional analysis, which assumes that the ICM is spherically...
Figure 2. Contour map of the inner part (11 \times 11 \text{arcmin}^2) of the 0.4–2.2 keV X-ray image, overlaid upon the optical image of the same area in the sky. The data have been quite heavily smoothed using a Gaussian kernel with dispersion of $\sigma = 30$ arcsec in order to reveal the large-scale distribution of gas in the system. The contour lines are from 10 to 100 per cent of the peak value, and are spaced logarithmically in intervals of 0.05 dex.

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Our X-ray image shows that the emission from the group can be traced out to $\sim 7.5$ arcmin ($\sim 1$ Mpc). The peak of the emission, which we use to define the centre of the cluster, does not coincide with the position of the galaxy, but lies $\sim 38$ arcsec to the south-west [RA = 04$^\text{h}$ 00$^\text{m}$ 52.2$^\text{s}$, Dec. = 34$^\circ$ 42$'$ 50.5 (J2000)], between the radio lobes. The surface brightness profile of the intracluster gas was obtained from an unsmoothed 0.4–2.2 keV image. Photons were counted in 20 concentric circular annuli around the cluster centre and extending out to the limits of the cluster. The width of each annulus was 22.5 arcsec. The emission from other point sources detected within the field was removed, and the background, taken from an annulus between 7.5 and 15 arcmin, was subtracted.

The observed X-ray emission from groups and clusters of galaxies can be well described, at least in their inner parts, by the hydrostatic-isothermal $\beta$ model (Cavaliere & Fusco-Femiano 1976). In this model, the surface brightness $I(R)$ at a distance $R$ from the peak of the emission is given by

$$I(R) = I_0 \left[1 + \left(\frac{R}{R_c}\right)^2\right]^{-3\beta + 1/2},$$

where $I_0$ is the peak brightness, $R_c$ is the core radius, and $\beta$ is the density index.
where \( I_o \) is the central surface brightness, and \( r_c \) defines the core radius. The index \( \beta \) is the ratio of the energy density per unit mass stored in the galaxies to the energy density per unit mass in the gas:

\[
\beta = \frac{\mu m_p \sigma^2}{kT_{\text{gas}}},
\]

where \( \mu \) is the mean molecular weight, \( m_p \) is the proton mass, \( T_{\text{gas}} \) is the temperature of the gas, and \( \sigma \) is the line-of-sight velocity dispersion of the galaxies (Gorenstein et al. 1978).

Our X-ray data were fitted by the model of equation (1), leaving \( I_o \), \( r_c \) and \( \beta \) as free parameters. The extracted counts from each annulus and the best-fitting model are presented in Fig. 3. We found a value for the \( \beta \) parameter of 0.9 ± 0.2, which is on the high side of the values found from Einstein observations of poor clusters of galaxies (\( \beta = 0.4-0.7 \): Price et al. 1991). This result indicates that the gas distribution is steeper and more centrally concentrated than in most of the groups and poor clusters of galaxies studied by Price et al. Interestingly, such a high \( \beta \) value was also found for the gas distribution in the 'fossil' group RX J1340 + 4018 (Ponman et al. 1994), which is similarly dominated by a single large elliptical galaxy. The other two parameters of the fit are: core radius \( r_c = (3.0 \pm 0.7) \) arcmin = (0.4 ± 0.1) Mpc; and \( I_o = (2.4 \pm 0.1) \) count pixel\(^{-1} \) (\( \chi^2 = 13.76 \) for 17 degrees of freedom). The central surface brightness can be converted to unabsorbed energy flux of the source, once we take into account the spectrum of the emitting gas and the galactic hydrogen absorption (see Section 4.2). This calculation yields \( I_o = (3.6 \pm 0.2) \times 10^{-6} \) erg s\(^{-1} \) cm\(^{-2} \). Previous X-ray observations (e.g. Price et al. 1991, Doe et al. 1995) have found the core radii of groups and poor clusters of galaxies to be less than 250 kpc; a value as large as 400 kpc is usually reserved for rich clusters (e.g. Jones & Forman 1984). However, larger than average core radii have been found in systems which show evidence of dynamical activity such as a recent merger event (e.g. Burns et al. 1995). Therefore, the large value for 4C 34.16 provides additional evidence that the ICM in this cluster has been recently disturbed, as is also implied by the appearance of the gas in the X-ray image (see also Section 4.1.2).

Inspection of Fig. 3 seems to indicate that the \( \beta \)-model does not fit the central points particularly well. Excesses in the central emission above the values predicted by the conventional \( \beta \)-model have previously been seen in many clusters of galaxies (e.g. Jones & Forman 1984, Edge, Stewart & Fabian 1992). Accompanied by a drop in gas temperature towards the cluster centre, these features have been attributed to the existence of cooling flows (Fabian, Nulsen & Canizares 1984, Fabian 1994). However, given the poor statistics in the current data, this central excess is not significant, and exclusion of the central points from the data set did not improve the fit.

The surface brightness distribution (equation 1) can be deprojected to give the number density profile of the gas if its temperature is known, and the ICM is assumed to be isothermal. This deprojection procedure yields

\[
n(r) = n_0 \left( 1 + \frac{r^2}{r_c^2} \right)^{-3\beta/2}.
\]

The central number density of the gas \( n_0 \) can be written as

\[
n_0 = \frac{I_o}{C \pi r_c} \left( \frac{3\beta/2}{\Gamma(3\beta/2)} \right)^{1/2},
\]

where \( \Gamma \) is the complete gamma function. The factor \( C \) is given by

\[
C = 1.42 \times 10^{-22} g T_{\text{gas}}(e^{-E_s/kT} - e^{-E_{s0}/kT}) \text{ cm}^{-3} \text{ erg s}^{-1} \text{ cm}^{-2},
\]

where \( g \) is the integrated Gaunt factor, \( T_{\text{gas}} \) is the temperature of the emitting ICM, and \( E_s - E_{s0} \) is the energy range covered by the PSPC. Assuming a gas temperature of \( kT_{\text{gas}} = 1 \) keV (Section 4.2), we find that the central number density is \( n_0 = (0.8 \pm 0.2) \times 10^{-3} \) cm\(^{-3} \). This number density is in agreement with the value obtained by Burns et al. (1981) in their analysis of the Einstein satellite observations of this cluster, and it is also consistent with the central densities found in other poor clusters of galaxies (e.g. Mulchaey et al. 1993; Doe et al. 1995).

Assuming that the emitting gas is bound by the gravitational potential of the cluster, we can calculate the 'binding mass' \( M_{\text{bind}}(r) \), which is the total mass of the cluster contained within a sphere of radius \( r \).

\[
M_{\text{bind}}(r) = \frac{3\beta kT_{\text{gas}}}{G \mu m_p} \frac{r^3}{1 + (rr_c)^2}.
\]

Values of \( M_{\text{bind}}(r) \) calculated for \( r = r_c, 2r_c \) and \( 3r_c \) are shown in Table 1, and are in the range of \( M_{\text{bind}} \) found in other poor clusters of galaxies (Kriss, Cioffi & Canizares 1983; Doe et al. 1995). All the calculated masses have errors of approximately 50 per cent of the mean value, mostly due to the uncertainty in the temperature (Section 4.2). It is well established from optical and X-ray observations that the luminous mass (stars + gas) can account for only a small fraction of the total mass needed to bind the group or cluster together. The gas mass is usually much less than 30 per cent
of the binding mass (Briel, Henry & Böhringer 1992). We calculate the gas mass \( M_{\text{gas}}(r) \) by integrating equation (3); for \( \beta = 1 \), we find

\[
M_{\text{gas}}(r) = 4\pi r^2 n(r) \rho(r)\frac{r}{[1 + (r/r_c)]^{1/2}} + \ln \left[ \frac{r}{r_c} + [1 + (r/r_c)]^{1/2} \right]
\]

(7)

Table 1 also contains the gas mass to binding mass ratio. The mean ratio we found lies in the range defined by previous X-ray observations (e.g. Price et al. 1991). We find no evidence for the increase with radius in the mass fraction associated with the ICM which has been found in other groups and clusters (David, Jones & Forman 1995). This difference arises from the large \( \beta \) factor which characterizes the gas distribution around 4C 34.16; for example, a value of \( \beta = 0.65 \) would give a gas mass within 3\( r_c \) five times larger than the tabulated value.

### 4.1.2 Substructure

Inspection of the X-ray emission in Fig. 1 reveals that the simple axisymmetric model of equation (1) is an oversimplification. The most striking and dominant feature in the ROSAT data is a strong 'wake' of X-ray emission between the radio lobes. Such structures in the ICM have been previously observed in other clusters of galaxies such as Abell 400 (Beers et al. 1992; Burns et al. 1994), Abell 2634 (Burns, Eilek & Owen 1982; Pinkney et al. 1993; Burns et al. 1994), the NGC 5044 group of galaxies (David et al. 1994), and the cluster which hosts the 1914 + 479 radio source (Pinkney et al. 1994). If we attribute the bending of the radio jets to the effect of ram pressure (see Section 5), we can identify the direction in which the radio galaxy is travelling relative to the ICM with the direction traced by the wake. Such a trailing wake occurs naturally as a consequence of the motion of the galaxy relative to the ICM: the ICM is focused downstream. This mechanism was first explored by Bondi & Hoyle (1944) in the context of stellar accretion (Bondi–Hoyle accretion). Hunt (1971) performed quantitative calculations of subsonic and supersonic accretion flows for the case of a point source moving through an adiabatic gas, simulating the relative motion of a galaxy through the ICM. Such a wake has also been noted as the source of the asymmetries in the X-ray emission from the Coma cluster, where even slow subsonic motion of one of the cluster's dominant galaxies through the surrounding ICM, with a velocity of \( \sim 200 \) km s\(^{-1} \), can account for the concentration of material behind the galaxy and the creation of a wake (De Young, Condon & Butcher 1980). Recently, more sophisticated three-dimensional simulations of Bondi–Hoyle accretion have been performed (Ruffert & Arnett 1994; Ruffert 1994, 1995, 1996). In these simulations totally absorbing spheres of varying sizes (from 0.01 to 10 accretion radii) move at speeds spanning from subsonic (\( M = 0.6 \)) to supersonic (\( M = 10 \)) relative to homogeneous media of different adiabatic indices. One of the most important results of these simulations is that they make it clear how sensitively the detailed structure of the perturbed medium depends on the initial conditions of each individual case. We therefore do not know in detail how the resulting structure (e.g., the density, length and age of the wake) will be affected if, for example, the 'totally absorbing sphere' were replaced by a more realistic galaxy model. It is important also to note that the results presented in these papers generally show the systems at the end of the simulations, when in most cases a steady state has been developed. Interestingly, in the early parts of these simulations all systems display a local density maximum downstream from the accretor, and these structures appear remarkably similar to the wake seen in our X-ray image.

A further strange feature in the X-ray emission is the ring apparent in Fig. 1 at a distance of \( \sim 2.5 \) arcmin from the galaxy. It is not clearly seen in Fig. 3, because it is not concentric with the annuli we used to obtain the surface density distribution of the ICM. However, this structure does appear to be statistically significant, and real (it is not, for example, an artefact from the PSPC window support ring). It appears remarkably similar to the lens-shaped shock front seen in simulated images of merging clusters (Schindler & Müller 1993; Schindler 1996). These features, together with the large core radius of the cluster, provide evidence for significant dynamical activity in the ICM around 4C 34.16, perhaps due to a recent merger event. We would not expect such an event to be as dramatic and violent as a collision between richer clusters, and it is more likely in this case that we are witnessing the infall of a cloud of gas into the poor group in which 4C 34.16 resides. Such an infall of relatively cool, possibly primordial, gas has already been mooted as the cause of the substructure seen in Abell 548 (Davis et al. 1995) and Abell 2597 (Sarazin et al. 1995).

### 4.2 Spectral analysis

Spectral analysis of the gas around the 4C 34.16 radio source was performed with the IRAF PROS 'XSPECTRAL' package. A circle centred at the cluster centre and extending out to 5.83 arcmin was used to extract the spectrum of the extended emission around 4C 34.16. The background region was specified by an annulus around the source region, and extended out to 12.5 arcmin. The point sources embedded in the source and the background regions were excluded. After background subtraction, the source region yielded 847 ± 50 counts.

The extracted spectrum was fitted by an absorbed Raymond–Smith (1977) thermal plasma model which takes into account the free–free continuum and the line emission from heavy elements. The model was convolved with the calibrated telescope and instrument response, and fitted to the data using the simplex minimization method. During the fit, the normalization, the temperature \( T_{\text{gas}} \), and the galactic hydrogen column density \( N_{\text{H}} \) were left as free parameters.
while the redshift, internal absorption and metal abundance were held fixed. We assumed a negligible internal absorption for an abundance of 40 per cent, in agreement with the abundances previously found in clusters of galaxies (e.g. Edge & Stewart 1991). Fig. 4 shows the extracted spectral data and the best-fitting spectrum, and Fig. 5 presents the confidence limits on the data and the best-fitting spectrum, and Fig. 5 presents the difference could either be an indication of a local excess in the hydrogen column density which is significantly greater than the value obtained from 21-cm observations (e.g. Johnstone et al. 1992). This difference could either be an indication of a local excess in the hydrogen column density can vary rapidly with position; since the beamwidth of the radio telescope which was used to map the atomic hydrogen distribution in the Stark et al. survey is 2°.5, any small-scale excess in the hydrogen column would not appear in their data. Under these circumstances our spectral fit is not able to give a reliable result for the gas temperature, since the source of the absorption is not clearly known. Throughout the remainder of this paper we adopt a credible temperature for the gas of $kT_{\text{gas}} = 1$ keV, and where necessary we state how our results depend on the adopted temperature.

An estimate of the unabsorbed X-ray luminosity at the rest frame of the cluster is given in Table 2. This luminosity was calculated assuming a hydrogen column equal to the value given by Stark et al. (1992); it is higher than the value calculated by Burns et al. (1981), because they did not include the absorption of the X-ray emission by the galactic hydrogen in their analysis.

5 THE BENDING OF THE JETS

The current view of the nature of the radio jets is that they are continuous flows of plasma emerging from the host galaxy. For WAT sources, which have the characteristics of Fanaroff & Riley class I radio sources (Fanaroff & Riley 1974), it is believed that the bulk plasma velocities can be characterized by non-relativistic velocities (Bridle & Perley 1984). Thus the radio jets in WATs obey the usual Euler equation, which describes the equation of motion of a volume element in the fluid:

$$\frac{\partial \rho}{\partial t} + (\mathbf{v} \cdot \nabla) \rho = \frac{1}{\rho_1} \left[ \nabla P - (\rho_{\text{gas}} - \rho) \mathbf{g} \right],$$

where $\mathbf{v}$ is the velocity of the jet, $\rho$ is the jet density and $\rho_{\text{gas}}$ is the density of the ICM. The forces acting on the jets are the following.

(i) The ram pressure ($\nabla P$) which is due to the relative motion of the galaxy through the ICM. Its amplitude is well approximated by

$$\nabla P = \rho_{\text{gas}} \frac{v_{\text{gal}}^2}{h},$$

where $v_{\text{gal}}$ is the galaxy velocity, $h$ is the unit vector in the direction of the galaxy velocity, and $h$ is the scaleheight of the jet (O’Donoghue, Eilek & Owen 1993).

(ii) The buoyancy $[-(\rho_{\text{gas}} - \rho) \mathbf{g}]$, where $\mathbf{g}$ is the gravitational acceleration of the cluster. Assuming that the gas is isothermal and in hydrostatic equilibrium within the gravitational potential of the cluster, $\mathbf{g}$ is given by the formula

$$\mathbf{g} = \frac{kT_{\text{gas}}}{\mu m_p} \frac{\nabla \rho_{\text{gas}}}{\rho_{\text{gas}}},$$

Equation (8) can be simplified by considering only the components of this vector equation which lie in the plane of the sky, and by resolving these components into ‘intrinsic’ coordinates, in which the axes are defined such that they always lie parallel and perpendicular to the jet. If we also assume a steady flow ($\partial \mathbf{v}/\partial t = 0$), we find that the perpendicular component of equation (8) at any point along the jet can be written

$$\frac{\rho_i}{R} = \frac{\rho_{\text{gas}}}{h} \frac{v_{\text{gal}}^2}{h} \mathbf{n} + \frac{(\rho_{\text{gas}} - \rho)}{\mu m_p} kT_{\text{gas}} \mathbf{v}_{\text{gal}} \cdot \mathbf{n},$$

Figure 4. The extracted total counts per energy channel and the best-fitting Raymond–Smith (1977) spectrum model (dashed line). Only the points which are marked with boxes were included in the calculations of the best-fitting model.

Figure 5. Confidence ellipses of the galactic $N_H$ versus the temperature $T_{\text{gas}}$ in the $\chi^2$ grid. Contours at 67, 90 and 99 per cent are shown.
where \( \hat{n} \) is the unit vector normal to the jet in the plane of the sky, \( R \) is the apparent radius of curvature of the jet at that point, and \( v_i \) and \( v_{\text{gal}} \) now refer only to the components of the jet and galaxy velocities in the plane of the sky.

Our radio map of 4C 34.16 (Fig. 1) shows clearly that the radio jets exhibit a double bend. Near the galaxy the jets are bent towards the cluster centre, but further downstream they change direction, travelling away from the cluster centre. The first bend can be attributed to ram pressure resulting from the relative motion of the galaxy through the ICM. At larger radii buoyancy takes over as the dominant force, and the jets change direction towards lower density regions in the ICM.

The interplay between these two forces provides a useful constraint on the velocity of the galaxy and the properties of the jets. At the turnover point (the point at which the bend in the jets changes direction and the radius of curvature becomes infinite), the components of ram pressure and buoyancy in the direction normal to the jet exactly balance, giving

\[
\rho_{\text{gas}} v_{\text{gas}}^2 \frac{\hat{n} \cdot \hat{v}_{\text{gal}}}{\hat{n}} = - \frac{(\rho_{\text{gas}} - \rho_g) k T_{\text{gas}}}{\mu m_p} v_{\text{gas}} \cdot \hat{n}.
\]

(12)

In this equation the only unknowns are the galaxy velocity, \( v_{\text{gal}} \), and the density of the jet at this point, \( \rho_j \); there is no dependence on the velocity of the jet. Thus we are able to calculate \( v_{\text{gal}} \) as a function of \( \rho_j \). The scaleheight \( h \), which is the width of the jet at the turnover point, can be measured from the width of the radio emission (suitably corrected for the resolution of the telescope). Fig. 6 shows the velocity of the galaxy as a function of the ratio of the density of the jet to the density of the ICM, \( \rho_j/\rho_{\text{gas}} \). As expected, we find that the density of the jets is less than the density of the ICM, at least at the turnover point. More interestingly, there is an upper limit on the galaxy velocity of 4C 34.16 relative to the ambient gas of \( v_{\text{gal}} \leq 300 \) km s\(^{-1} \). Due to the uncertainty in the gas temperature (Section 4.2) we conducted the same calculations with a gas temperature of 2 keV. The resultant galaxy velocity is also shown in Fig. 6 (dashed line). The increase in the permitted galaxy velocity can be understood by noting that as the temperature of the ICM becomes higher, buoyancy becomes more effective. Consequently, ram pressure must increase to balance buoyancy. Since the dependence of the gas density on the temperature is not very strong, an increase in the ram pressure must be accompanied by an increase in the galaxy velocity.

We should also recall that \( v_{\text{gal}} \) measures only the velocity of the galaxy in the plane of the sky. If the galaxy also has a significant line-of-sight component to its velocity, then the total speed of the system will be somewhat higher. In principle, of course, the line-of-sight component can be measured directly by comparing the redshift of the galaxy to the average of other cluster members. However, the paucity of this cluster would render such a measurement very difficult in practice.

As was mentioned in the introduction, large elliptical galaxies are expected to reside at the minimum of the cluster gravitational potential. Optical observations support this expectation, with high-velocity dominant galaxies found only in merger environments (Bird 1994). Beers et al. (1995) have reported redshifts for 23 poor clusters of galaxies; they find an offset in the central galaxy velocity from the mean velocity of the rest galaxies in the groups of \( \leq 150 \) km s\(^{-1} \) for groups which show no evidence for subclustering or contamination from foreground and background galaxies. The required galaxy velocity we found for 4C 34.16 is higher than this limit, but not as high as was previously calculated from the dynamics of other WAT sources (e.g. Burns 1981). Such a moderate velocity could easily arise in the sort of merger event suggested by the spatial analysis (Section 4.1).

Away from the turnover point, the shape of the jets also depends on the jet velocity \( v_j \). We can thus obtain an estimate of the velocities of the jets in this system by applying equation (11) to a part of the jet closer to the galaxy. The results of such an analysis are presented in Fig. 7, which shows a plot of the predicted jet velocity versus the \( \rho_j/\rho_{\text{gas}} \) ratio. In our calculations we used a galaxy velocity of \( v_{\text{gal}} = 300 \) km s\(^{-1} \) (solid line), and \( v_{\text{gal}} = 400 \) km s\(^{-1} \) (dashed line) as was inferred from the above analysis. The radius of curvature at that point measured from our radio map is \( R = 50 \) arcmin and the scaleheight \( h = 37.5 \) arcsec. In agreement with the jet velocities calculated in other ‘C’ shape radio sources using similar arguments (Bridle & Perley 1984), the derived velocity for the jet is restricted to low values.

### 6 THE WAKE

The presence of the wake in the X-ray emission provides further evidence that 4C 34.16 is moving at a modest velocity relative to the ICM, as required if the radio jets are to be bent by ram pressure. In this section, we investigate whether the observed properties of the wake are consistent with the derived limits on the galaxy velocity.

The range of galaxy velocities we found implies that the galaxy is moving subsonically relative to the ICM, since the speed of sound in an adiabatic gas of temperature 1 keV is
We also know that the characteristic length-scale for Bondi–Hoyle accretion, the accretion radius $R_a = 2GM_{gal}/v_{gas}^2$ (Hunt 1971), is large in this system: for a massive elliptical galaxy moving at $\sim 300$ km s$^{-1}$, we find $R_a \approx 100$ kpc. Thus $R_a$ is larger than the physical extent of the galaxy itself (see Section 3). For such a system in which a small accretor moves subsonically through gas, the gas flow is dictated by the gravitational attraction of the accretor and the relative motion between the accretor and the medium. Thus a simple ballistic model provides a good approximation for estimating the properties of 4C 34.16. In such a model the gravitational concentration of material by the motion of a galaxy, the overdensity $\Delta n$ at a distance $b$ from the axis along which the galaxy is moving is given by

$$\Delta n \approx \frac{2GM_{gal}}{v_{gal}^2} n, \quad (13)$$

where $n$ is the ambient gas density, and $M_{gal}$ is the mass of the moving galaxy (Chandrasekhar 1943). Thus, if we know the overdensity of the wake, we can see if the estimate of the galaxy’s velocity is consistent with a sensible value for its mass.

In order to calculate the density of the wake its temperature is needed. Unfortunately, the number of counts from the small region of the wake is not sufficient to constrain the full spectral fit. A simpler indication of the temperature is provided by the mean energy per photon. Calculating the mean energy for photons coming from the wake ($E_{wake}$) and for photons coming from the surrounding ICM ($E_{ICM}$), we find that $E_{wake} = 1.08 \pm 0.09$ keV, and $E_{ICM} = 1.03 \pm 0.03$ keV. These results indicate that the temperature of the wake is not very different from the temperature of the surrounding ICM, and so we adopt a value of 1 keV.

Assuming that the gas in the wake emits via thermal bremsstrahlung its luminosity ($L_{wake}$) is proportional to its density ($L_{wake} \propto n_{wake} T^{5/2}$). By choosing a rectangular source region within which the wake is located, and a background region from immediately outside the enhanced wake, we can calculate the excess unabsorbed luminosity due to the wake in the rest frame of the source, $L_{wake}$. This analysis yields $L_{wake} = (1.2 \pm 0.4) \times 10^{43}$ erg s$^{-1}$, assuming a galactic $N_{H}$ equal to the Stark et al. value. Consequently, the density of the wake is found to be $(1.6 \pm 0.3) \times 10^{-3}$ cm$^{-3}$, which exceeds the central density of the gas by $\Delta n = (0.8 \pm 0.3) \times 10^{-3}$ cm$^{-3}$.

As a characteristic value for $b$ in equation (13), we adopt the half-width at half-maximum of the wake, $b \approx 30$ arcsec. If the elliptical galaxy which hosts 4C 34.16 is moving at a speed of 300 km s$^{-1}$, which is an average value of the galaxy velocities that we found in Section 5, then equation (13) implies that the elliptical galaxy must have a mass of $\sim 10^{12} M_{\odot}$ in order to reproduce the observed wake overdensity. This value is consistent with what we would expect for a giant cluster elliptical, and so the observed properties of the wake do indeed seem consistent with what we would expect from this simple gravitational focusing model. This ballistic model is clearly an oversimplification, since it neglects the gaseous properties of the ICM. A more thorough treatment would involve comparing the data with full hydrodynamic simulations, but the quality of the data really do not justify such careful comparisons. All we can say at this point is that the consistency with the simple model suggests that it has captured the essence of the underlying physics.

## 7 SUMMARY

We have presented radio, optical and X-ray observations of the field which contains the WAT source 4C 34.16. In our radio map, 4C 34.16 appears as a very symmetric radio source. Its jets exhibit a double bend, with their ends directed away from the peak of the X-ray emission. As predicted on the basis of its steep radio spectrum, 4C 34.16 is confined by an ICM which we detected in the X-ray data. Our spectral analysis indicates that the gas is relatively cool, although it is difficult to assess the exact temperature due to the apparent excess of absorption by cool atomic gas implied by the fits. The results of our spatial and spectral analysis are summarized in Table 2.

Analysis of the X-ray data revealed substantial substructure in the gas, strongly reminiscent of the images simulated by Roetttinger et al. (1993) and Schindler & Müller (1993) for merging clusters of galaxies. In particular, the X-ray emission is elongated; the X-ray image revealed a faint outer ring of emission, which could be the ‘lens-shaped’ shock front pointed out by Schindler & Müller (1993) and Schindler (1996), generated after the collision of the two subclumps; and there is a wake which can be explained as arising from the gravitational focusing of the ICM by the motions of the central galaxy which have been induced by

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>0.078</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>$r_c$</td>
<td>$(0.4 \pm 0.1)$ Mpc</td>
</tr>
<tr>
<td>$n_0$</td>
<td>$(0.8 \pm 0.2) \times 10^{-3}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$kT_{gas}$</td>
<td>~ 1 keV</td>
</tr>
<tr>
<td>$L_{\delta}(0.2 - 2.2$ keV)</td>
<td>$2 \times 10^{43}$ erg s$^{-1}$</td>
</tr>
</tbody>
</table>
the merger. The large core radius of the X-ray emission is also unusual for a poor cluster dominated by a single central galaxy, but is expected in a system that has undergone a recent merger.

The direction of motion of the galaxy, as inferred from the position angle of the wake and the direction in which the radio jets are bent, coincides with the direction in which the X-ray emission is elongated on larger scales. This coincidence is exactly what we would expect if the merger produced large-scale streaming of gas in the direction in which the subclusters collided, producing the relative motion between the ICM and the galaxy that is required to bend the jets in the WAT radio source by ram pressure.

In fact, the combination of ram pressure and buoyancy provides a credible explanation for the double bend in the jets in 4C 34.16. By using the X-ray data to measure the properties of the ICM which cause these bends, we can obtain strong constraints on the remaining unknown quantities, the velocity of the galaxy, and the properties of the jets themselves. By looking just at the point where buoyancy and ram pressure forces balance, we can obtain a strong upper limit on the velocity of the galaxy, which implies that it is moving at \( \lesssim 300 \text{ km s}^{-1} \). Such a relative velocity between the galaxy and the ICM might credibly be induced in the minor cluster merger scenario that we have discussed above. We have also shown that a large elliptical galaxy moving at such velocities would induce the wake-like density enhancement in the ICM that we observe.

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