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B2 1637+29, A MASSIVE RADIO GALAXY PROBING A POOR BUT GAS-RICH GROUP

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ABSTRACT

The radio galaxy B2 1637+29 has very unusual properties which are particularly enigmatic given the absence of any obvious cluster of galaxies. VLA observations show a very distorted radio tail, which starts with an apparent oscillation (or undulation) with a projected wavelength of 100 kpc and then strongly curves back. Such structure is unusual even in a rich cluster, but galaxy counts in this region indicate that the radio galaxy is probably a member of a very poor group. However, a significant amount of gas ($\geq 10^{13}$ $M_\odot$) has to be present in order to produce the long radio tail, and for this reason B2 1637+29 is probably the dominant member of a galaxy-poor but gas-rich cluster.

A CCD image reveals that the optical counterpart is a double galaxy with the radio jets emanating from the nucleus of the brighter of the two galaxies. Spectroscopic observations indicate a radial velocity difference of $\sim$4300 km s^{-1}, which is very high if this is a bound system. Both galaxies are intrinsically very bright and have an absolute magnitude typical of cD galaxies. Since a chance superposition at an angular distance of 10″ is highly improbable in a region of low galaxy density, one has to assume that the two galaxies are physically close, in spite of the very large velocity difference.

The unusual radio structure is explained by two independent physical effects: (1) the motion of a radially orbiting galaxy at its apogee leads to the sharp bend at the outer part of the source and (2) the physical encounter between the two massive galaxies modulates the jet ejection velocity causing the asymmetry in brightness and the undulation in the tail.

Subject headings: galaxies: clustering — galaxies: individual (B2 1637+29) — galaxies: intergalactic medium — radio sources: galaxies

I. INTRODUCTION

The radio source B2 1637+29 is a member of the faint B2 sample of low-luminosity radio galaxies (Fanti *et al.* 1978). A 12 hr observation at 1.4 GHz with the Westerbork Synthesis Radio Telescope (WSRT) revealed a most unusual ringlike structure (see Parma, Ekers, and Fanti 1985), the optical counterpart (an elliptical galaxy with $m_v = 14.8$ and $z = 0.0875$) being displaced $\sim 1'$ from the brightest part of the ring.

B2 1637+29 was reobserved at the VLA with higher resolution and better sensitivity. Also, a CCD image was obtained and, as the optical identification turned out to be a double galaxy, spectra of both galaxy nuclei were taken. The new observations are briefly described in § II.

The environment of the radio galaxy is discussed in § III, while a description of the radio source morphology is given in § IV. We show that B2 1637+29 is the dominant member of a poor group of galaxies and argue that it moves with an average velocity of a few hundred km s^{-1} with respect to an intergalactic gas cloud with mass $\geq 10^{13}$ $M_\odot$. In § V the relevance of the environment of the radio galaxy to the source morphology is discussed and we propose an explanation for the highly peculiar features, such as the undulation in the radio tail and the difference in both length and brightness of the main and counter jet. Finally, in § VI we summarize the main results of our investigation.

II. THE NEW DATA

a) The Radio Data

Most B2 low-luminosity radio galaxies have now been observed with the VLA (Parma *et al.* 1986; de Ruiter *et al.* 1986; Fanti *et al.* 1986; Fanti *et al.* 1987). Because of its interesting radio structure, as seen in the WSRT map (Parma, Ekers, and Fanti 1985), B2 1637+29 was selected for a more detailed study with the VLA (for a description of the VLA see Napier, Thompson, and Ekers 1983). The observing log is given in Table 1.

The data were reduced in the way described by Parma *et al.* (1986). A detailed analysis of the radio data, including the spectral index distribution and polarization, will be given in a forthcoming paper.

In Figure 1 (Plate 8) the image obtained by combining the 1.4 GHz high- and low-resolution data is shown as a composite radio photograph. The 1.4 GHz low-resolution data alone emphasize the diffuse low-brightness radio emission; the corresponding contour map is shown in Figure 2.

b) The Optical Data

A CCD image, taken in 1985 June with the 1.5 m Loiano telescope (Bologna), establishes beyond doubt that the optical counterpart of the radio source consists of two, and perhaps three, separate galaxies (see Fig. 3). The difference in magnitude

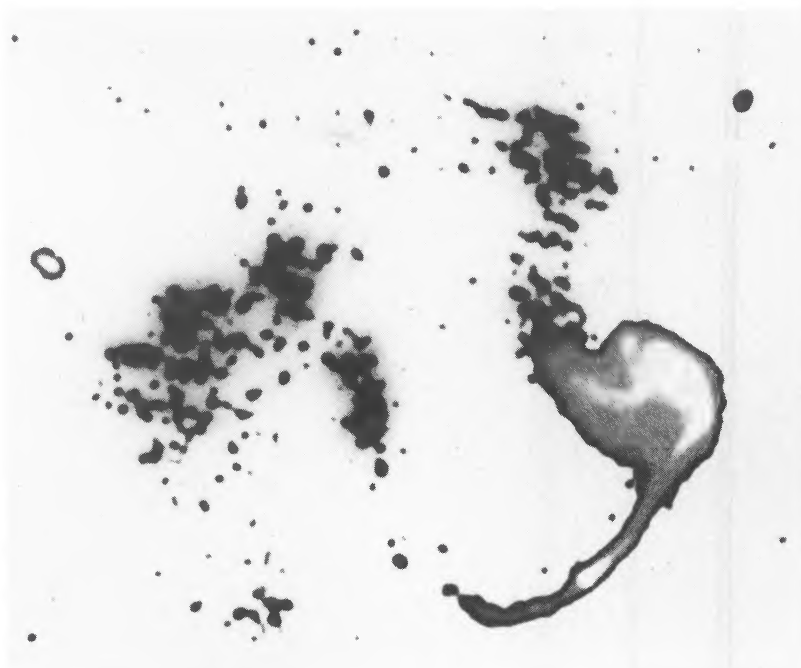

FIG. 1.—Radio image of B2 1637+29, obtained by combining the 1.4 GHz high- and low-resolution data (3″.5, B + C)

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TABLE 1

PARAMETERS OF THE VLA OBSERVATIONS

Observing Date	Frequency (MHz)	VLA Configuration	Observing Time	Resolution	Noise (mJy)
1981 Sep 24	1465	B	$5^{hr}48^{min}$	3".5	0.06
1983 May 03	4885	C	$6^{hr}34^{min}$	3.5	0.03
1983 May 05	1465	C	$5^{hr}22^{min}$	11.5	0.15

between the two brightest galaxies is ~0.7 mag, the brighter (southern) object coinciding with the radio core. The third object is ~2 mag fainter, and its nature is uncertain: in the following we will consider only the two bright galaxies. Their separation is 10", which corresponds to a linear projected distance of 12 kpc (here and in the following a Hubble constant of 100 km s^{-1} Mpc^{-1} is used).

A spectrum, with a dispersion of 104.5 Å mm^{-1}, was taken with the IPCS on the Isaac Newton Telescope (La Palma observatory) in 1987 June. The long slit covered both nuclei simultaneously; the observing time was 10 minutes. In both galaxy spectra several absorption lines are easily recognized (the H and K lines, the G band, Hβ, and the Mg I triplet). Thus we find for the radio galaxy $z = 0.0880 \pm 0.0001$, similar to the value $z = 0.0875$ given by Fanti *et al.* (1978), and for its companion $z = 0.1034 \pm 0.0004$. This corresponds to a velocity difference between the two galaxies of 4260 ± 120 km s^{-1}; we will discuss the velocity difference and the question of physical association in the next section. The interval between 4000 and 5000 Å of both nuclear spectra is shown in Figure 4. Some of the identified lines are indicated. In the following, intrinsic parameters (e.g., luminosity) are calculated using the redshift of the radio galaxy.

III. THE ENVIRONMENT OF B2 1637+29

On the Palomar Sky Survey no obvious cluster is visible of which B2 1637+29 might be the first ranked galaxy. There are four or five relatively bright galaxies (with $m_v \sim 15.5$–16) within a radius of ~15', but their redshifts are unknown. Apparently the galaxy system is rather isolated; it is just inside the outer contour of the Zwicky cluster 1635.9+2939 (medium compact, near), but the redshift of B2 1637+29 is so high that its membership in a near cluster is unlikely. In order to get a better idea of the environment of B2 1637+29 we counted objects in an area with radius ~20' down to the plate limit of the red Palomar Sky Survey print ($m_{lim} \approx 20$). Since faint stars and galaxies are very difficult to distinguish, we counted all objects irrespective of their morphology. The distribution of objects with $m_r < 17.3$ is uniform: the few bright galaxies present inside a 15' radius from B2 1637+29 do not show up in the overall statistics of bright objects. On the other hand, there is a tendency for fainter objects to be concentrated

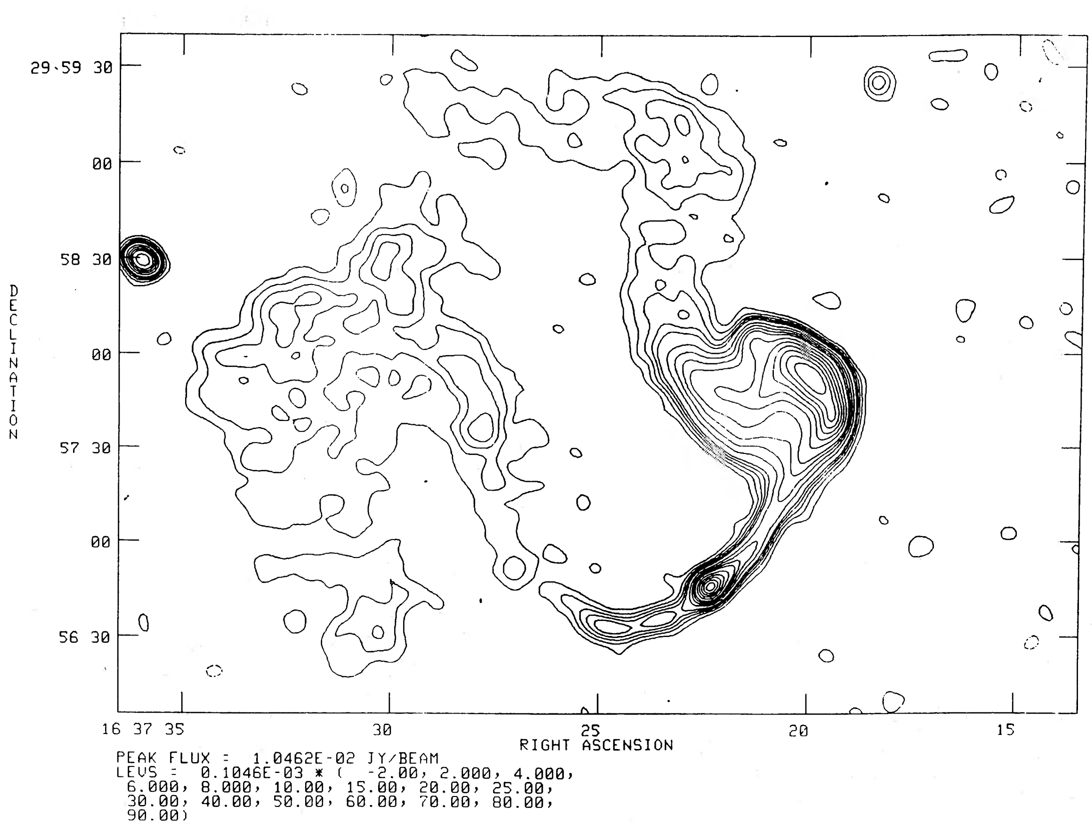

FIG. 2.—Contour map of 1.4 GHz low-resolution image (6".5, B + C). Contour levels are −0.2 (*dashed line*), 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, and 9.0 mJy per beam.

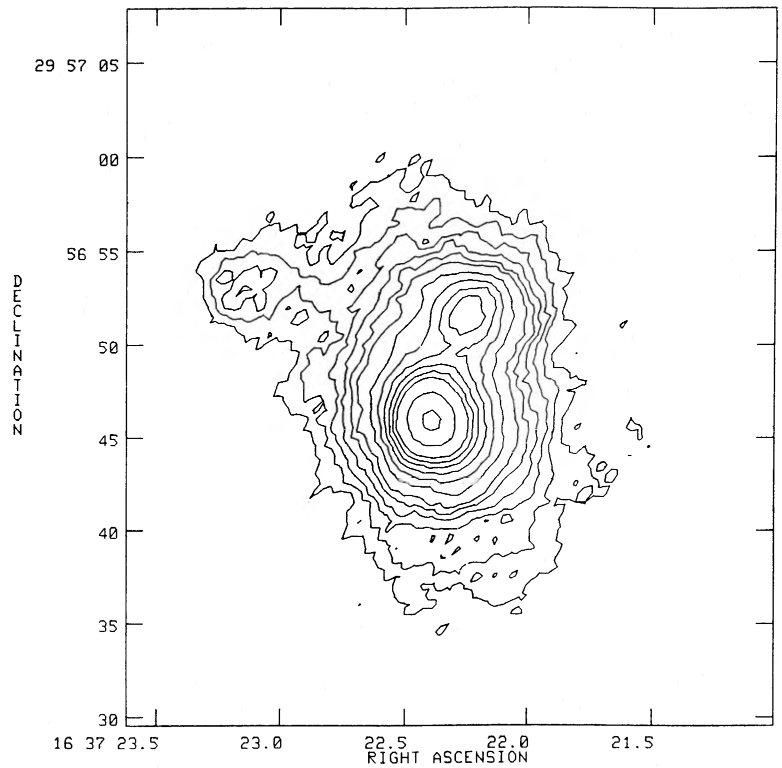

FIG. 3.—CCD image (through an *R* filter) taken with the 152 cm telescope at Loiano (Bologna). The radio source is associated with the brighter (southern) galaxy.

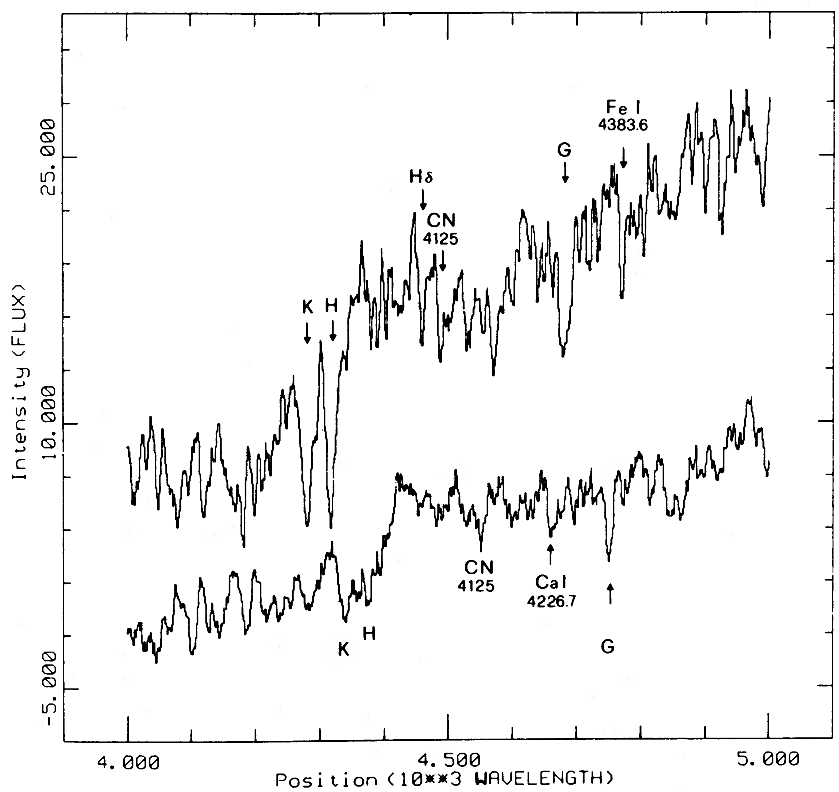

FIG. 4.—Spectra of the nuclei of the radio galaxy (*upper spectrum*) and its companion (*lower spectrum*); only the range 4000–5000 Å is shown. The flux scale is in arbitrary units.

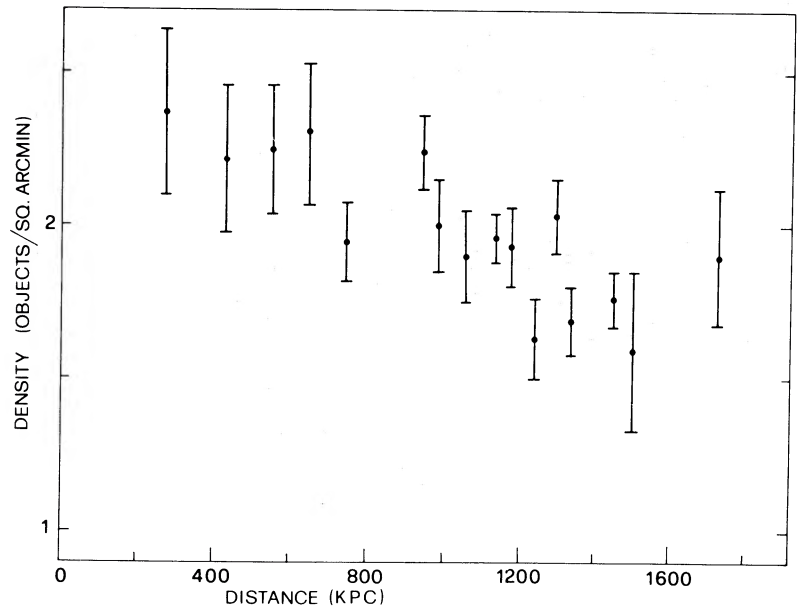

FIG. 5.—Counts of faint ($m_r > 17.3$) objects on the red Palomar Sky Survey print, around B2 1637+29

around the radio galaxy, as can be seen in Figure 5; the average density excess is $\sim$0.4 objects arcmin^{-2} (i.e., $\sim$25%). If we ascribe this density enhancement entirely to galaxies that belong to the same cluster as B2 1637+29, then this cluster contains in total about 300 galaxies above the sky survey limit within a 15′ radius (which corresponds to a linear radius of $\sim$1 Mpc at the redshift distance of the radio galaxy). We emphasize that the density enhancement is largely due to very faint objects, with $m_r > 17.3$ ($m_v > 18.5$, see Fanti *et al.* 1978), i.e., at least 4 mag fainter than the B2 1637+29 galaxies. Because there are very few galaxies in the vicinity of the radio galaxy with brightness within 2 mag of B2 1637+29, it is likely that the radio galaxy is the dominant member of a poor group of galaxies, very similar to the poor groups studied by Morgan, Kayser, and White (1975), and Albert, White, and Morgan (1977). In fact, depending on which of the relatively bright galaxies belong to the cluster, the richness class is -3 or -2 (see Bahcall 1980). If the Zwicky cluster was misclassified as near, the B2 1637+29 poor group may actually be a substructure of a larger cluster.

The large velocity difference of 4300 km s^{-1} naturally poses the question of whether the apparent double galaxy is a chance superposition of two unrelated galaxies. The absolute magnitudes of the radio galaxy and its companion were determined using the diameter-magnitude calibration for elliptical galaxies on Palomar Sky Survey (PSS) prints given by Fanti *et al.* (1978). The brighter galaxy has $M_v = -22.3$, and the fainter, $M_v = -21.6$; there is therefore no doubt that *both* galaxies are giant ellipticals, with a magnitude typical of a first ranked cluster galaxy.

If the galaxies are unrelated, we are faced with a situation in which two giant ellipticals are by chance separated by only 10″. This is very unlikely: there are five bright galaxies in the vicinity of B2 1637+29, and if we assume that these galaxies are randomly distributed in a volume of 1 Mpc^3 centered on the radio galaxy, there is a probability of 2×10^{-3} that at least one of them falls within a projected distance of 12 kpc (corresponding to 10″). If the bright galaxies belong to different clusters they may of course occupy a much larger volume, and the probability for a chance coincidence will be even lower. Therefore, we prefer to investigate in more detail the alternative, that the two galaxies are physically associated and their interaction causes the unusual radio structure.

IV. THE RADIO SOURCE

a) General Remarks on Radio Morphology

B2 1637+29 is a low-luminosity radio galaxy, with radio power $10^{24.4}$ W Hz^{-1} at 1.4 GHz, and is expected to have a distorted and relaxed radio structure, as indeed it does. Moreover, as is common in this type of source, a very well defined two-sided jet connects the radio core with the outer emission regions.

More unusual for a low-luminosity source is the strong asymmetry in brightness between the two radio lobes, due to the high-brightness region where the west jet bends and terminates.

Perhaps most striking is the overall morphology. As a whole the radio source has the appearance of a narrow-angle tail (like NGC 1265, O'Dea and Owen 1986). The east jet can be traced out to a projected distance of 50 kpc, whereas the west jet reaches a length of 75 kpc out to the point where it starts to widen, brighten, and curve strongly (see Fig. 1). On both sides the jets bend and go over into low-brightness regions that show sinuous undulations; the eastern trail finally curves back sharply (Fig. 1). The undulation in the western trail (Fig. 2) has a projected wavelength of $\sim$100 kpc.

b) The Radio Jets

We assume that the overall shape of B2 1637+29 is due to interaction of the radio source with an intergalactic medium (IGM), i.e., the diffuse emission regions are the trails of the source. Estimates of the initial and final jet velocities can be obtained from the well-known relation for head-tail sources (see Burns and Owen 1980):

$$\frac{\rho_J v_J^2}{R_J} = \frac{\rho_{\rm IGM} v_g^2}{r_J}\,, \tag{1}$$

where R_J is the radius of curvature of the jet and r_J is the jet diameter. In the west jet we have $R_J \sim 130$ kpc and $r_J \sim 2.6$ kpc in the first 70″, and $R_J \sim 15$ kpc and $r_J \sim 10$ kpc beyond 70″. The galaxy velocity with respect to the IGM is not known, but if the velocity is lower than ~ 500 km s^{-1} the age of the outer regions becomes high ($\geq 5 \times 10^8$ yr) and we would expect to see a considerably stronger steepening of the spectral index than has been observed: from a comparison of the 1.4 and 5 GHz data (to be published elsewhere) we find that in the outermost regions $\alpha \sim 1$. An average velocity much higher than 500 km s^{-1} seems unrealistic. Therefore we write $v_5 = v_g/(500 \text{ km s}^{-1})$; defining $\eta = \rho_J/\rho_{\text{IGM}}$ we get for the west jet an initial velocity $v_{J,\text{init}} \sim 3500 v_5 \eta^{-1/2}$ km s^{-1}, and a final velocity $v_{J,\text{final}} \sim 600 v_5 \eta^{-1/2}$ km s^{-1}. Similarly, the initial radius of curvature of the east jet gives $v_{J,\text{init}} \sim 2000 v_5 \eta^{-1/2}$ km s^{-1}.

The strong deceleration of the jet is confirmed by the behavior of the jet opening angle as a function of distance from the core and by the jet brightness as a function of jet diameter since both imply a change in the flow velocity of the jet (see Fanti *et al.* 1982 for a discussion of jet velocities).

From these simple considerations we can already draw some important conclusions. The decrease of the jet flow velocity by a factor of 6 is, as can be seen from equation (1), mainly established by the difference in curvature of the jet close to the core and at the outer end. Assuming a jet pressure $P_J \sim \rho_{\text{IGM}} v_g^2$, the initial Mach number, estimated from the radius of curvature (Begelman, Rees, and Blandford 1979), strongly suggests that the jet initially is highly supersonic, with $M > 5$. By the time the jet starts to bend it has $M \sim 1$, and its velocity has become comparable to that of the galaxy. Furthermore, putting $v_5 = 1$ we find the external density $\sim 4 \times 10^{-4}$ cm^{-3}.

The temperature of the external medium can be estimated from the minimum pressure in the low-brightness regions ($\sim 10^{-12}$ dyn cm^{-2}); assuming that these regions are confined by the external thermal pressure we derive $T_{\text{IGM}} \sim 10^7$ K.

V. DISCUSSION

a) The Head-Tail Structure

Since B2 1637+29 generally has the aspect of a narrow-angle tail (NAT) source, it is natural to assume that the bending of the radio jets is due to interaction of the radio-emitting material with an IGM. However, there is one crucial difference: normally NATs are associated with ordinary cluster ellipticals, and wide-angle tails (WATs) with the dominant galaxy of a cluster. It has been argued that cD galaxies, and in particular WATs associated with dominant cluster galaxies, should be almost at rest with respect to the cluster gas (see, e.g., Burns, Gregory, and Holman 1981; Burns 1983). On the other hand, Fanti (1984) has shown that WATs can have velocities that are significantly different from the mean cluster velocity. A similar conclusion, based on completely different arguments, was reached by Malamuth (1987): in one of his simulations of poor clusters the cD galaxy reaches a final velocity of 676 km s^{-1} with respect to the cluster. It should be remarked that in this case Malamuth used a radial distribution of galaxy velocities.

The sharp bending of the outer part of the source, which occurs at ~ 200 kpc from the core, may be less mysterious than it seems at first sight if the orbit of B2 1637+29 is eccentric: it represents the point where the radio galaxy starts to move back into the cluster after having risen out of the cluster potential well by ~ 200 kpc.

b) The Double Galaxy System and the Cluster Environment

The very large velocity difference between the two galaxy components of B2 1637+29 poses an interesting question. Obviously, the galaxies would need to have very large masses to be bound: for a minimum distance of 15 kpc the relative velocity then requires a mass $> 3 \times 10^{13}$ $M_\odot$ within that distance. For this reason it is also possible that they are unbound and follow different eccentric orbits in the cluster potential well. A case for eccentric orbits was made by Tonry (1984, 1985*a*, *b*), based on the excess, in rich clusters, of close companions of dominant galaxies with large velocity differences. According to Tonry, the high percentage of companions (30%–50%; see Hoessel 1980; Schneider, Gunn, and Hoessel 1983) can be explained this way. However, we should remark that the double galaxy system cannot be very far from forming a bound system since the interaction between the two galaxies must be quite strong to cause the peculiar radio structure, and this implies large masses in addition to close proximity.

Tonry (1985*b*) also noted that the brightest cluster galaxies show a lack of low-velocity nuclei in their vicinity and concluded that they may already have captured all slow-moving neighbors, such that their total luminosity rises above $2L^*$, where L^* is the optical luminosity at the break in Schechter's luminosity function (Schechter 1976). Now, B2 1637+29 consists of two highly luminous galaxies: the radio galaxy itself has $L \sim 7L^*$, and its companion $L \sim 3.5L^*$. Their velocity difference is ~ 3 times the maximum difference found by Tonry (1985*b*), and, moreover, the galaxies are located in a poor cluster environment. For these reasons we believe that B2 1637+29 may be an extreme case of the picture sketched by Tonry (1985*a*, *b*), although the issue of eccentric orbits is controversial (see, e.g., Smith *et al.* 1985 or Cowie and Hu 1986). We mention in passing that AWM 5, one of the poor clusters studied by Bahcall (1980), contains a dominant galaxy with an absolute magnitude similar to that of B2 1637+29. The lack of other bright galaxies in its vicinity may, according to Bahcall, be the result of cannibalism. Another poor group (MKW 8) contains a double galaxy system. So B2 1637 + 29 may be a rare specimen, in particular because of the associated radio source, but not unique.

A bound orbit in the cluster (with a velocity of 500–1000 km s^{-1} with respect to the cluster) requires a cluster mass of $\geq 10^{13}$ $M_\odot$. The large majority of galaxies in the B2 1637+29 cluster are faint and the total contribution of galaxies to the cluster mass is between 10^{12} and 10^{13} $M_\odot$, for an assumed M/L ratio of 10. This may be just sufficient to bind the radio galaxy to the poor cluster, but, as indicated by the radio source, a gas with density $\sim 10^{-4}$ cm^{-3} and $T \sim 10^7$ K, filling a volume with radius ~ 1 Mpc (see Fig. 5), is also present. The total mass in the form of gas is then at least of the order of $\sim 10^{13}$ $M_\odot$; this is not unreasonable at all for a poor cluster as can be seen from the X-ray observations of poor clusters discussed by Kriss, Cioffi, and Canizares (1983).

c) Undulations and Asymmetries in the Radio Structure

At this point the undulations and the brightness asymmetry remain to be discussed. Oscillations, or wiggles, are often found in radio sources associated with multiple nuclei, and dynamical models have been applied in a number of cases, e.g., 3C 31 (Blandford and Icke 1978), 3C 130 (Jägers and de Grijp 1985). For a general discussion on radio sources in double galaxy systems we refer to Wirth, Smarr, and Gallagher (1982).

For B2 1637+29 we propose the following scenario, which might explain, at least in a qualitative way, the observed radio structure:

1. The radio galaxy is falling inward, toward the center of the cluster. The radio tails left behind trace the orbit of the radio galaxy in the cluster; the ends of the tails (beyond the strong bending seen at ~ 200 kpc from the present position of the galaxy) were produced at the time when the radio galaxy was still rising out of the cluster potential well.

2. The radio galaxy has approached another, slightly less massive, galaxy, which in its turn is moving with respect to the cluster center. Apparently we are seeing the two galaxies at the moment of closest approach (or close to it).

3. As the two galaxies come closer and start to interact gravitationally, the velocity vector of the radio galaxy will change both in magnitude and direction. This will cause the radio galaxy to deviate from its unperturbed orbit and will strongly influence the jet velocity with respect to the IGM. In order to understand this, let us assume that the radio galaxy is accelerated in such a way that the galaxy velocity becomes comparable to the jet velocity and has a significantly large component along the ejection axis of the radio source. Then, in one direction along the radio axis, the two velocities will add up (producing the west jet), but, in the opposite direction, the galaxy velocity must be subtracted from the jet velocity (this gives the east jet). Thus, even if the intrinsic ejection velocities of the east and west jet are equal, the actual velocities may be significantly different due to the interaction of the radio galaxy and its "companion." In § IV*b* a velocity of $\sim 3500(v_g/500)$ km s^{-1} was determined for the west jet and a velocity of $\sim 2000(v_g/500)$ km s^{-1} for the east jet. A simple calculation shows that this difference may indeed be due to the encounter of the two galaxies: ignoring projection effects, the velocity difference of 4300 km s^{-1} between the two galaxies during flyby may be produced, if we assume a hyperbolic orbit with velocities at infinity (i.e., in the outer parts of the cluster) of 500 km s^{-1} for both galaxies. The total mass in the galaxies needed to give a relative velocity of 4300 km s^{-1} is then $3 \times 10^{13}\ M_\odot$ (assuming that flyby occurs at a separation of 15 kpc), which means a mass of $2 \times 10^{13}\ M_\odot$ for the radio galaxy and $1 \times 10^{13}\ M_\odot$ for its companion. Since the radio galaxy is twice as massive, its velocity with respect to the IGM will have changed by ~ 1000 km s^{-1}; assuming for simplicity that this change takes place along the jet axis, the velocity difference between the two jets will be ~ 2000 km s^{-1}. This is indeed the right order of magnitude: the east jet moves only slowly with respect to the IGM at the moment of flyby and may therefore be shorter and less luminous than the west jet, which has received an extra push to make it longer and brighter.

Of course, the interaction does not take place instantaneously; its effect on the radio structure gradually becomes more important, leading to the formation of the western high-brightness region. The extra "push" to the west jet also provides a natural explanation for the undulation in the western tail (since the west jet gradually penetrates farther into the IGM, it produces an apparent undulation in the tail). Indeed, the high-brightness region is more distant from the core than expected from the rest of the western tail, and this is precisely what gives the impression of an oscillation. Due to the faintness of the east jet, the effect is more difficult to see at that side.

Because of the large number of degrees of freedom, accurate fits reproducing the radio source are not very meaningful, but, in any case, the source structure can be understood qualitatively.

What makes the radio source unusual are the extreme curvature of the tails and the undulation combined with the large difference in brightness between the two sides, The extreme curvature is unusual, not because of our proposed explanation—eccentric (or radial) orbits in poor clusters may be quite common even for dominant galaxies (Malamuth 1987)—but because it is seen. The undulation is exceptional because it points so clearly to the gravitational interaction of two probably unbound galaxies as the cause for the distortion of the radio structure. The combination of the two effects and the special environment—a poor cluster—make this radio source different from almost all others. Its special properties enable us to study the dynamics of a poor cluster in more detail than would otherwise be possible: if the tail indeed traces part of the eccentric orbit of the radio galaxy we have, as it were, a photograph of the orbit itself.

VI. CONCLUSIONS

In summary, we believe that two independent physical effects have acted together to produce the observed radio structure, projection effects being implicitly recognized as a major cause for distortion of the three-dimensional image.

The first factor is a nonuniform motion of the radio galaxy with respect to an intergalactic medium. Motion in an eccentric orbit leads not just to the—quite common—radio tails, but to a sharply curved radio trail, if the outer part was ejected when the radio galaxy was still rising out of the cluster potential well. The size of the radio galaxy orbit and the electron density derived from the curvature of the jets give a total mass of the gas cloud of $\geq 10^{13}\ M_\odot$. Even with few galaxies present, such a cloud can be self-gravitating at a temperature of 10^7 K. Indeed, the cloud mass, its temperature, and the electron density as derived from the radio source agree well with the observations of other poor clusters by Kriss, Cioffi, and Canizares (1983). Confirmation of the presence of such a gas cloud will have to await future X-ray observations.

The second effect is due to the encounter of a radio galaxy with another massive galaxy; it causes the conspicuous undulation in the western radio tail and the high brightness of the west lobe. This effect can only work if the velocity of the galaxy is high, and if the galaxy changes the direction of the velocity vector significantly. The large velocity difference between the radio galaxy and its companion suggests that the hypothesized encounter may be a realistic possibility.

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