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3C 129 CLOSE-UP

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ABSTRACT

High-resolution VLA observations of the head-tail radio galaxy 3C 129 have shown thin, faint streams connecting the nucleus to the larger tails. The multiple bends and wiggles in the source are easily described in terms of precessing beams, as shown in a companion *Letter* by Icke. As in NGC 1265, the jets can be mildly supersonic or mildly relativistic. We point out the major features of these curved streams and their importance for general models of extragalactic jets.
Subject headings: galaxies: intergalactic medium — galaxies: nuclei — radio sources: galaxies

I. INTRODUCTION

In recent years, head-tail radio galaxies have become members of the "jet set," that is, sources with thin streams of radio emission connecting their nuclei and extended tails. In 3C 129, a one-sided jet was observed by Owen *et al.* (1979), but only a curious bright spot was seen at the start of the western tail. The higher-sensitivity VLA observations presented here reveal a faint, curved stream extending from (near) the nucleus to the western tail. Head-tail jets are important because their considerable bending and persistent collimation can help us understand the momentum flux and stability conditions in these structures. The remarkable stability of the western stream, through bends $>90°$, stands as a theoretical challenge. In this *Letter*, we present new maps of 3C 129 showing this structure and briefly explore some of its possible consequences. We assume, as all do, that 3C 129 is in a fairly rich galaxy cluster, although its low galactic latitude ($b_{II} = 0\overset{\circ}{.}1$) allows only the few brightest galaxies to be seen in the Palomar Sky Survey. *OSO 8* observations in this direction (see summary by Mushotzky and Smith 1980) reveal an X-ray source of comparable temperature, and slightly lower luminosity (1/5) than in the Perseus cluster, home of the famous head-tail source NGC 1265.

II. WHAT DO WE SEE?

The VLA radio pictures (Fig. 1*a*, λ6 cm, and Fig. 1*b*, λ20 cm [Pl. L6]) show only the first 40″ and 4′, respectively, of this ~20′ long source. The observations leading to these "cleaned maps" are summarized in Table 1. References to other maps of 3C 129 are listed in Table 2, to provide more quantitative information.

To set the scale, the western stream is 31″ (13 kpc) long in projection, using Spinrad's (1975) redshift of 0.021 and $H_0 = 75$ km s^{-1} Mpc^{-1}. The eastern tail is $\lesssim 0\overset{''}{.}8$ (0.3 kpc) in width near the nucleus. Low signal-to-noise ratio prevents any useful limits on the western thin stream width. The compact, flat-spectrum nuclear source has a flux density of ~33 mJy and is burned out on the λ6 cm plate at the southeast source extremity. The surface brightness just north of the nuclear source is ~2 mJy per $0\overset{''}{.}9 \times 0\overset{''}{.}6$ beam at λ6 cm. The western stream curves sharply into a bright ridge, and there is some hint that it persists further into the tail. The long baseline 20 cm visibility data were weighted down to produce the low-resolution (6″) map presented here. The peak on this map is 42 mJy, including contributions from the nuclear source and the eastern stream. Complex radio brightness/displayed brightness transfer functions have been used to enhance interesting features in these pictures.

a) Symmetry/Asymmetry

On scales of 10″–30″, the twin tails of 3C 129 are very similar in size, shape, and brightness. This is in stark contrast to the picture seen at high resolution, where the thin streams near the nucleus are quite dissimilar. The final bend in the western thin stream shows that projection alone cannot account for these differences. Different forces acting on the two beams will give rise to different shapes and arise naturally when the ejection of the streams is at an angle which is *not* perpendicular to the motion of the galaxy through the intracluster medium. This force asymmetry arises both in models where the jets couple directly to the intracluster medium (e.g., Begelman, Rees, and Blandford 1979, hereafter BRB) or through pressure gradients in the interstellar medium (Jones and Owen 1979, hereafter JO). Symmetric NGC 1265 is actually an anomaly in this regard.

At 10″–30″ resolution, the average surface bright-

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a)

b)

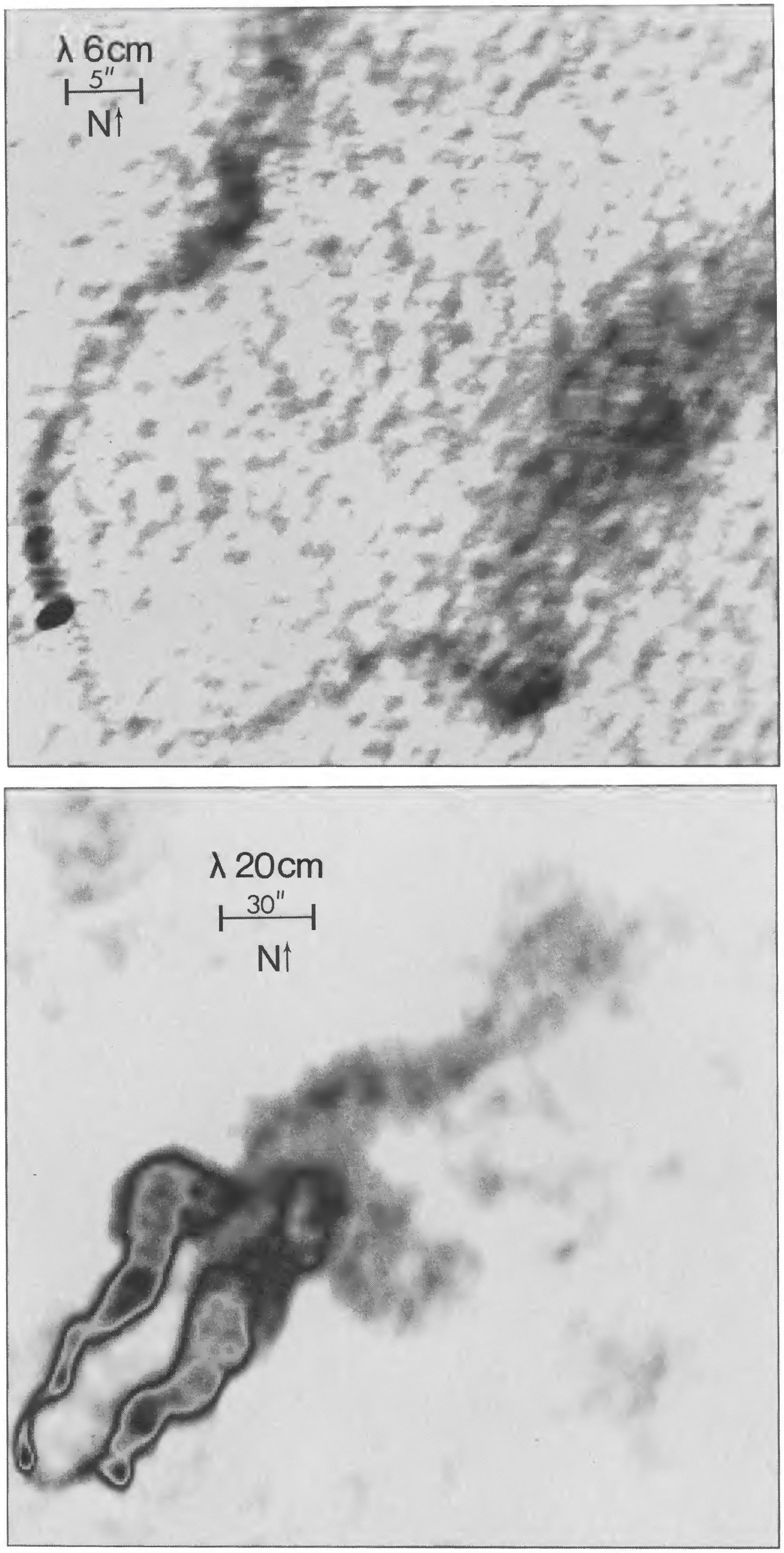

FIG. 1.—(*a*)–(*b*) VLA radio pictures at λ6 cm (*top*) and λ20 cm (*bottom*) of the front of the head-tail source 3C 129. The resolution (clean beam size) is 0″.9 × 0″.6 at −35° position angle and 6″ × 6″, respectively. The displayed brightness levels are a complicated function of observed brightness. More quantitative information can be obtained from the references in Table 2.

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nesses of the two tails differ only by ~20%. However, at 1″–2″ resolution, the eastern jet is 2–3 times brighter, on average, than the western one, at both λ6 cm and λ20 cm. Unlike the stronger classical double sources, relativistic enhancement may not be important here (but also see below).

The appearance of radio jets is often described in terms of "inefficiencies" of the underlying beam, that is small bits of the energy flow "leaking out" as synchrotron radiation on its way to the extended tails. Assuming that projection effects are not important, we first note that the brightness of the thin jets must be *incidental* to the main energy supply, since the large-scale structure is so symmetric. Second, the fainter western stream has a higher initial velocity with respect to the external medium, and more severe curvature, than its brighter eastern counterpart. This is contrary to our naive expectations. For example, if Kelvin-Helmholz instabilities (which depend on the velocity difference between the jet and the external medium) trigger the synchrotron emission, then the western jet should be brighter. As a caveat to these conclusions, we must remember that projection effects can sometimes affect the surface brightness distribution.

TABLE 1

VLA Observing Parameters

Parameter	λ20 cm	λ6 cm
Epoch[a]	1979 Sept. 14	1979 Sept. 15
Frequency	1.48 GHz	4.88 GHz
Bandwidth	12 MHz	12 MHz
Number of antennas	14	17
Spacings[b]	0.06–17.2 km	0.06–17.2 km
Taper[c]	5 km	none

[a] Source and calibrator (DA 193) tracked $\pm 6^h$ from transit, each band.

[b] Unprojected values. This was an interim, hybrid configuration of the VLA, with two antennas used close in on the north arm and the rest split between east and west arms.

[c] Width of Gaussian visibility taper, for the maps presented in Figures 1*a* and 1*b*.

TABLE 2

3C 129 Maps

Freq. (MHz)/ Band (cm)	Resolution	Reference
43/698	14′.9×5′.6	1
73.8/407	4′.8×4′	1
408/73.5	163″×115″	2
610/49	79″×56″	3
1407/21.3	32″×23″	4
1415/21.2	32″×23″	5
1480/21.3	6″×6″	this *Letter*
2700/11.1	17″×12″	6
2700/11.1	5″.2×3″.7	7
2695/11.1	9″.7×6″.3	8
5000/6	9″.2×6″.5	9
5000/6	10″×7″	10
4886/6	1″.5×1″.5	11
5000/6	10″×7″	12
4885/6	0″.9×0″.6	this *Letter*
8085/3.7	3″.2×2″.1	8

References.—(1) Perley and Erickson 1979. (2) MacDonald, Kenderdine, and Neville 1968. (3) van Breugel 1980 [Harris and Miley data]. (4) Hill and Longair 1971. (5) Miley 1973. (6) Riley 1973. (7) Downes 1979. (8) Rudnick *et al.*, in preparation. (9) Riley 1973. (10) van Breugel and Miley 1977. (11) Owen *et al.* 1979. (12) van Breugel 1980.

b) Bends and Wiggles

Curved radio structures are now rather common. Oscillations in structure can be due to orbital motions of the parent galaxy, as in 3C 31 or 3C 449 (Blandford and Icke 1978). Rotational symmetry may be the result of precessing beams (see, e.g., Miley 1980). Helical instabilities (Hardee 1979) may play a role in a variety of astrophysical jets (e.g., M87, Owen, Hardee, and Bignell 1980; Hardee 1981).

In 3C 129, the *overall* curvature is explained by relative motion through the intracluster medium. However, the quasi-periodic undulations in each of the streams require another cause. The orbiting black hole model of Valtonen and Byrd (1980) does not predict (but may allow) the curious initial shape of the western stream. The orbiting galaxy scenario is unlikely for 3C 129, because no sufficiently massive companion is present. The helical instability model has yet to be investigated for tailed sources. Precession of the nuclear source in 3C 129 was suggested by van Breugel and Miley (1977); a quite reasonable case has now been made (Icke 1981) based on the current data. This may require massive orbiting black holes inside the galaxy, as suggested by Begelman, Blandford, and Rees (1980).

c) Nature of the Jets

The bending of 3C 129's jets [curvature radius (R)/jet width$(h) \gtrsim 25$] implies mildly supersonic flows in either the models of BRB (where, from eq. [2], the jet Mach number $M_j = (R/gh)^{1/2} \gtrsim 5$, g = specific heat ratio) or JO$(M_j \sim 1)$. The important difference between these two models is the assumed pressure drop across the jet. This pressure drop is equal to the ram pressure from the intracluster medium for BRB, but is reduced by a factor of ~(jet width/interstellar medium scale) for JO. The equipartition pressure of the relativistic material in the jets is $\gtrsim 10^{-10.5}$ dyn cm^{-2}, as in NGC 1265. The ram pressure available from the intracluster medium is at most on the same order, assuming an X-ray inferred density of $\sim(1\text{–}10) \times 10^{-4}$ cm^{-3} and a relative velocity for 3C 129 of $\sim 10^{3.5}$ km s^{-1}. Thus, as argued by BRB, the relativistic particles and fields cannot be far from equipartition, and any thermal material in the jet cannot dominate its internal pressure. Both the BRB and the JO models require these conditions so that the available external pressures can confine the jets.

Table 3 summarizes the various observational constraints on these models if we allow the flow speed and/or the internal equation of state to be relativistic. The relativistic generalization of the BRB model has been derived from JO equation (6), with the pressure

TABLE 3

OBSERVATIONAL CONSTRAINTS ON THE FLOW IN 3C 129'S JETS

JET EQUATION OF STATE	JET PRESSURE GRADIENT	
	$\rho_{IGM}v_{gal}^2/r_j$ (BRB)	$\rho_{IGM}v_{gal}^2/r_{ism}$ (JO)
Non-relativistic (cold)......	$M_j \approx (1/\gamma_j)(R/gr_j)^{1/2} \gtrsim 5/\gamma_j$ $\gamma_j \approx 1$, implies supersonic flows $\gamma_j > 2$–3, *not* allowed[a,b]	$M_j \approx 1/\gamma_j$ $\gamma_j \approx 1$, implies trans-sonic flow $\gamma_j > 1$, *not* allowed[a]
Relativistic...	$\gamma_j\beta_j \approx \frac{1}{2}(R/r_j)^{1/2} \gtrsim 2$–3	$\gamma_j\beta_j \sim 1$

NOTE.—ρ_{IGM} = intergalactic medium density; v_{gal} = relative velocity of 3C 129 with respect to IGM, r_{ism} = interstellar medium radius; r_j, M_j, β_j, γ_j, g—see text.

[a] This condition arises because M_j is by definition >2 when the material is cold, but the flow is relativistic.

[b] Not a strict limit; see text.

drop across the jet set equal to its internal pressure (p_j). Writing this pressure as $p_j = \rho_j v_s^2/g$ and substituting $\rho_j c^2$ for the nonrelativistic enthalpy, one obtains BRB equation (2) (T. Jones, private communication). The jet density is ρ_j, v_s its sound speed, and the distinction between jet radius and scale height has been ignored. The factors $\beta_j[\equiv v_j(\text{jet velocity})/c]$ and $\gamma_j \equiv (1 - \beta_j^2)^{-1/2}$ account for the possible relativistic flow speeds, and the enthalpy must be replaced by $4p_j$ if the equation of state is also relativistic. The results in Table 3 show that relativistic flow speeds are consistent with the observed bending, with even higher speeds possible in the BRB model. We wish to emphasize that bending itself does not rule out relativistic flows, as is sometimes assumed. The bent jets may then be very similar to straight jets, except for their environment.

The Table 3 estimates are somewhat uncertain. For BRB, the critical parameter is the width of the jet, which for 3C 129 is still unresolved for the first 25″ (10 kpc). If the jet is much narrower than the current limits, higher relativistic flows are allowed. In the JO model, M_j is independent of the jet width, and the scale of the interstellar medium is the important factor. Such a medium might be detectable with high-resolution, low-energy ($\lesssim$1 keV) X-ray observations. These arguments do not enable us to decide the form of the momentum flux, i.e., the relative contributions of mass density and velocity. Other workers (BRB; JO; Bridle, Chan, and Henrikson 1981 [BCH]) have tried to resolve this ambiguity by assuming that the kinetic energy of the flow is tapped to power the observed synchrotron source; we do not consider that question here.

Unlike NGC 1265, there is no sudden "ballooning" of the eastern tail, as can be seen from Figure 2. This could imply a very gentle transition from the interstellar to intergalactic medium or, perhaps, no substantial interstellar medium at all. This situation creates difficulties for the JO picture where the galaxy's turbulent wake powers the far tail region. Unfortunately, the tail width is still unresolved within ~10 kpc, where such a transition in the medium (and expansion of the tail) might be expected (JO; Lea and De Young

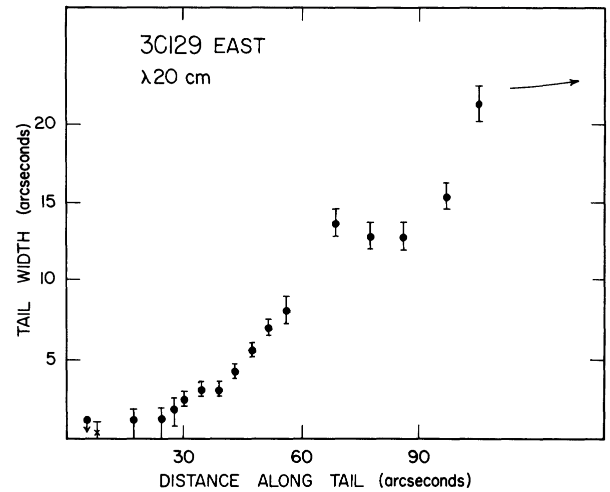

FIG. 2.—The plotted points indicate the full width half-maximum across the eastern tail of 3C 129 as a function of distance along the tail from the nucleus. These values have been determined from an *untapered* λ20 cm map and roughly corrected for convolution with the ~2″.5 beamwidth across the tail. The arrow on the right side of the figure points to the measurement of the width in the far tail, as measured from the λ21 cm map in Miley (1973). The point plotted as X was measured from the λ6 cm map discussed here.

1976). The rapid expansion of the western tail could signal the disruption of an overly twisted stream, but also might be misleading due to projection effects.

As found for the straight jet in NGC 315 (BCH), the eastern tail in 3C 129 (Fig. 2) shows evidence of increased collimation with distance from the galaxy. This is best seen from the large-scale 21 cm maps by Miley (1973), where transverse expansion of the source is effectively halted past 4′ from the head. The width of a typical component far down the tail was measured from Miley's map and is indicated in Figure 2. This "increased collimation," or decrease in opening angle, is perhaps a misnomer here, because the material in the tails may be *at rest* with respect to the external medium. Static confinement (pressure balance) then results in a constant width for this left-behind material.

Figure 2 also shows the suggestion of a second, smaller plateau at ~60″ from the nucleus. Such a plateau could arise, as described by BCH, by a two-component external medium, in this case, interstellar and intracluster. These authors have also discussed the dynamic role which can be played by magnetic fields. As a caveat, we note that the true narrowing of a jet and the simple addition of a small bright component can be hard to distinguish, especially since true narrowing itself can lead to an increase in brightness. Resolution of this ambiguity depends upon very good resolution of the jet.

The opening angle of the wiggles (=wiggle amplitude/distance down tail) stays fairly constant for the first 4′ of 3C 129, until they are no longer visible. Precession would result in such a constant opening angle, but only if the material in the streams were *not* stopped with respect to the external medium. It will therefore be important to consider models for 3C 129 in which material continues flowing down the tail after being deflected by the intracluster medium. Eventually, the amplitude of precessing wiggles must converge, because of the narrowness of the far tail regions.

As a final curiosity, we note the sharp drop in surface brightness (from $\gtrsim 0.5$ mJy arcsec^{-2} to $\lesssim 0.15$ mJy arcsec^{-2}) and possible disappearance of one tail, at a distance of $2'$ from the nucleus. In the northern low surface brightness region the wiggles continue and lead to the far tail, while the eastern region shows no structure and does not connect with any other part of the source. These features were also suggested in the observations by Downes (1979) and can be seen in the work of van Breugel (1980).

d) *Optical Appearance*

The interaction of 3C 129's parent galaxy with the intracluster medium and the possible presence of black holes in its nucleus raises the question of optical activity. Examination of the red Sky Survey glass copies reveals a number of filamentary structures surrounding the galaxy, somewhat reminiscent of the active galaxy NGC 1275 (Minkowski 1957). The apparent extension of the galaxy to the northwest, visible in the finding chart published by Hill and Longair (1971) is a blue stellar object, which could be a foreground star.

III. SUMMARY

We summarize the important consequences of these observations as follows:

1. The bending of 3C 129's thin streams does not preclude mildly relativistic flow speeds, whether or not an interstellar medium is present. If the flow speeds are not relativistic, then they are trans-sonic or mildly supersonic.
2. The asymmetry of the thin streams suggests that the observed synchrotron radiation is incidental to the main energy supply and not related in a simple way to the interaction of the jets with the external medium, assuming no strong projection effects.
3. The pronounced bends and wiggles in the stream can be easily explained by a precessing nuclear source (Icke 1981), which may imply massive orbiting black holes inside the galaxy. Other possibilities, e.g., helical instabilities, need to be explored.
4. The optical appearance of the galaxy is quite disturbed and merits close comparison with the radio structure.
5. Models of radio jets, and especially the problems of collimation and stability, will find a useful test in 3C 129 because of the strong initial curvature in the presence of a large-scale intracluster medium, the question of where the jets are stopped, and the possible precession. This work involves analysis of the polarization and spectral index data as well and is in progress.

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