3C 129 at 90cm: Evidence for a Radio Relic?

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ABSTRACT

We present a new wide-field map of the radio galaxy 3C 129 and its companion galaxy 3C 129.1 at $\lambda = 90$ cm. We see a distinct steep-spectrum feature near the head of 3C 129, extending in a direction perpendicular to the radio tails. We propose that this Crosspiece might consist of fossil radio plasma, which has been re-energized by the compression of the bow shock of the supersonically moving galaxy 3C 129. One possible origin of the fossil radio plasma could be the tail of a nearby head-tail radio galaxy. We discuss the implications of, and give testable predictions for, this scenario.

Subject headings: galaxies: active — galaxies: clusters: individual (4U 0446+44) — galaxies: individual (3C 129, 3C 129.1) — galaxies: jets

1. Background

The radio galaxy 3C 129 and its companion 3C 129.1 are part of an X-ray galaxy cluster at z=0.021 (4U 0446+44). The cluster lies in the galactic plane (b= 0.5^o, l= 160^o) and is only known to include one other member galaxy (WEIN 048) which lies to the south of 3C 129 (Nilsson et al. 2000). Because of their latitude, the cluster and the radio sources have been excluded from many optical studies.

Both radio sources have jets extending beyond their elliptical host galaxies and into the intracluster medium (ICM). 3C 129 shows prototypical narrow-angle-tail (NAT) morphology, with a plume-like double-tail extending nearly 30' at $\lambda \sim$ 90 cm. It has a total flux density of $\sim$ 5.3 Jy at 1400 MHz (White & Becker 1992). 3C 129.1, although considerably smaller, is a wide-angle-tail (WAT) source, with a total flux density of $\sim$ 1.9 Jy at 1400 MHz (Condon et al. 1998).

ROSAT X-ray data place the cluster center just to the southwest of 3C 129.1. The X-ray contours are slightly elongated in the East-West direction, suggesting that the cluster may have undergone recent merger activity. In addition, the X-ray contours are distorted near the brightest part of 3C 129; Leahy and Yin (2000) suggest that this may be caused by the radio plasma moving through the ambient cluster gas at speeds greater than the local speed of sound. The large-scale morphology of 3C 129 bends in a manner which is inconsistent with a naive tracing of its trajectory in the cluster potential. Cowie and McKee (1975) propose that buoyancy of the radio plasma in the ICM atmosphere may have helped shape the radio tail. This would imply that 3C 129 can be used to test the mechanical properties of radio plasma.

2. Data

During the late 1990's we obtained roughly 175 "snapshot" observations of this source using the Very Large Array (VLA)[1], each lasting a few minutes. The data at 330 MHz were intended to provide phase-referencing information for simultaneous observations at 74 MHz. Slightly more than half of the data were taken in A-array; the rest are nearly equally divided between B- and C-arrays. Standard calibration observations were used, and the data were mapped using wide-field imaging techniques in AIPS. The resulting image, shown in Figure 1 has nearly complete UV-coverage and roughly 8" resolution at a frequency of 330 MHz. The rms noise in the map is ~ 0.75 mJy, and the signal-to-noise ratio is S/N~ 400

3. Sources A, B, and C

The two faint sources marked A and B also appear in low resolution 74 MHz maps of this source (K. Blundell 2002, in prep.). Comparison with the 74 MHz image gives a spectral index $\alpha \approx 2.4$ for both sources ($S \propto \nu^{-\alpha}$). Neither source appears in the NVSS catalogue (Condon et al. 1998). The 2.5 mJy detection limit of that catalogue implies spectral indices $\alpha \geq 1.7, 2.1$ for sources A and B respectively, in agreement with the 74 MHz index. We suggest that these faint sources are two buoyant radio lobes produced by earlier activity of 3C 129.1. Their comparable sizes, luminosities, and similar distances to 3C 129.1 support this conclusion. Future measurements of their high frequency radio spectral cutoffs would provide a date for the corresponding phase of 3C 129.1, and provide an estimate of the buoyant rise velocity of these old lobes.

[1]operated by The National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Source C is too faint to be detected in the existing 74 MHz data. It is identified in the NVSS catalogue as a 3.2 mJy point source. In our 330 MHz map it is slightly extended, and has an integrated flux of 27.8 mJy. Combining these two fluxes we calculate a spectral index $\alpha = 1.5$. This source is coincident with the optical galaxy WEIN 047, and is also an IRAS source.

4. The Crosspiece

Figure 2 shows a contour image of the region near the head of 3C 129. There is a very clear feature just behind the head of the radio source, and running perpendicular to the tails. Its nature is still uncertain, but it appears to extend over both tails, so we will refer to this as the Crosspiece.

The contours in figure 2 are at multiples of the 3σ noise level in the map itself: it is clear both that the Crosspiece is highly significant and that there are no other suspiciously deep holes or bright regions in the area. Further confirmation of the reality of this feature was found in a paper by Jägers & de Grijp (1983) who made an early map of this source using the Westerbork Synthesis Radio Telescope at a wavelength of $\lambda \sim 50$ cm. They identify a small projection on one side of 3C 129 which corresponds in position to the Crosspiece. Using a zeroth order beam size correction, we estimate a spectral index between 330 MHz and 600 MHz of $\alpha \approx 3$ ($S \propto \nu^{-\alpha}$).

Although the estimate is imprecise, it is clear that this feature is very steep spectrum. Few other radio maps of this source exist at intermediate frequencies, but there are some high quality maps at $\lambda \sim 6$ cm (Taylor et al. 2001). Not unexpectedly if the feature is truly steep spectrum, these show no hint of the Crosspiece. The only existing map at 1400 MHz (Jägers 1987) is of very poor quality; we have recently received time to make a new one (Harris et al. 2002, in prep.).

4.1. A Scenario for the Crosspiece's Genesis

What then is the nature of the Crosspiece? It is always possible that it is simply a background radio source which happens to lie along the same line of sight as 3C 129. Given its steep spectrum nature, it would most likely be a high-redshift radio galaxy or possibly even a cluster. However its large angular extension (3'-4') makes this seem somewhat unlikely. The location and orientation of the Crosspiece near the head of 3C 129 suggests a physical connection between the two. In the following we introduce a possible formation scenario and discuss its implications.

The morphology, the low surface brightness, and the steep spectrum clearly distinguish the Crosspiece from the usual radio plasma outflow of 3C 129. It has more similarities with a so called *cluster radio relic*. Cluster radio relics are steep spectrum radio sources, typically located in peripheral regions of galaxy clusters, which need not be associated with any parent galaxies (for a review of the observations, see Feretti & Giovannini (1996)). These radio relics are believed to trace shock waves in the ICM and most likely consist of shock compressed fossil radio plasma (Enßlin, Biermann, Klein, & Kohle 1998; Roettiger, Burns, & Stone 1999; Enßlin & Gopal-Krishna 2001; Kassim et. al. 2001; Enßlin & Brüggen 2001).

Remnant radio plasma which is not too old is able to revive its radio emission after a shock compression (Enßlin & Gopal-Krishna 2001). Because the fossil's radio plasma internal sound speed is likely to be much higher than a typical cluster shock speed, the compression is adiabatic. Nevertheless, the compression factor can be high due to the soft equation of state of relativistic plasma (Pressure $\sim$ density$^\gamma$ with a soft $\gamma_{\rm rel.} \approx 4/3$ instead of the nonrelativistic less compressable $\gamma_{\rm non-rel.} = 5/3$), and the high energy cooling cutoff of the still relativistic electron population can be shifted adiabatically to observable energies. The simultaneous amplification of the magnetic fields during the compression also increases the characteristic synchrotron frequency of the highest energy electrons. This relic formation scenario has recently been supported by the morphological agreement between numerically simulated and observed cluster radio relics (Slee et al. 2001; Enßlin & Brüggen 2001).

4.2. Theoretical Considerations

Here we propose that the bow shock of 3C 129 itself might have revived the radio emission of the Crosspiece. In order to explain the bending of 3C 129's jets, a velocity of 3C 129 with respect to the ICM of $v_{\rm gal} = 500 - 3000$ km s^{-1} is assumed by various authors (Cowie & McKee 1975; Doe, Ledlow, Burns, & White 1995; Leahy & Yin 2000). The ICM sound velocity is $c_{\rm s} = 1217 \pm 22$ km s^{-1} for the cluster temperature of $kT_{\rm ICM} = 5.5 \pm 0.2\,{\rm keV}$ (Leahy & Yin 2000), and a Helium mass fraction of $\chi_{\rm He} = 0.25$, so 3C 129 could have a Mach number as large as $M = v/c_{\rm s} \leq 2.5$. 3C 129's Mach cone should therefore have a minimum opening angle of $\theta_{\rm Mach} \geq 2\,{\rm arcsin}(M^{-1}) \geq 50°$. This angle would increase if 3C 129's velocity is lower.

In order to heat a cold infalling plasma to the cluster temperature, $kT_{\rm ICM}$, in an accretion shock wave, the typical infall kinetic energy per particle has to be $E_{\rm inf} = \frac{\mu}{2}\, v_{\rm inf} \equiv \frac{3}{2}\, kT_{\rm ICM}$, where μ is the mean molecular mass of the gas. Therefore the infall velocity of matter onto the cluster must be $v_{\rm inf} \approx \sqrt{3\, kT_{\rm ICM}/\mu} = 1630$ km s^{-1}. This corresponds to a (post-accretion shock) Mach number of $M = 1.34$. 3C 129 is a member of an infalling galaxy cluster and could have an additional velocity component due to the infalling cluster's internal velocity dispersion. Nevertheless, we believe that a velocity close to the typical infall velocity is more likely than $v_{\rm gal} > 2500$ km s^{-1}.

3C 129's line-of-sight velocity $v_{||}$ should be given by the difference between its redshift ($z_{\rm 3C129} = 0.020814$) and that of 3C 129.1 ($z_{\rm 3C129.1} = 0.022265$). The latter is located at the cluster's X-ray center, has a nearly symmetrical radio appearance, and is therefore very likely to be at rest with respect to the cluster. Because the line-of-sight velocity for 3C 129 estimated in this way, $v_{||} = 435\,{\rm km\,s}^{-1}$, is low compared to the typical infall velocity, the supersonic motion of 3C 129 should be close to the plane of the sky (19° for Mach number $M = 1$, 13° for $M = 1.4$, and 7.5° for $M = 2.5$). Therefore, if the Mach cone can be assumed to be fully visible, projection effects of the revived fossil radio plasma should not have significantly altered its apparent (sky-projected) opening angle.

A visual inspection of the radio map (see Fig. 2) suggests an opening angle of $\theta_{\rm Mach} \approx 90°$, corresponding to $M = 1.4$ or $v_{\rm gal} = 1720$ km s^{-1}. We note that that the underlying assumption of this estimate, the full appearance of the Mach cone in the radio map, is not necessarily true, because the radio morphology can be affected by the morphology of the revived radio plasma. Nevertheless, the Crosspiece's morphology looks suggestive, and the derived velocity seems reasonable because it is close to the typical infall velocity of the cluster.

In order for the radio emission to be revived at a frequency of at least $\nu = 1420$ MHz, where we see part of the Crosspiece (Harris et al. 2002, in prep.), the radio plasma must be younger than

$$t_{\rm max} = \frac{39\,{\rm Myr}\,C^{2/3}}{(u_B + u_{\rm cmb})/({\rm eV\,cm^{-3}})}\sqrt{\frac{B/\mu{\rm G}}{\nu/{\rm GHz}}}. \quad (1)$$

(Enßlin et al. 2001). Otherwise the spectral cutoff is below the observing frequency. The terms $u_{\rm cmb} = 0.26\,(1+z)^4\,{\rm eV\,cm^{-3}}$ and $u_B = B^2/(8\,\pi) = 0.025\,(B/\mu{\rm G})^2\,{\rm eV\,cm^{-3}}$ denote the CMB energy density and the magnetic field energy density before the radio plasma compression. The compression factor is called C, and can be estimated from pressure equilibrium with the environment before and after the passage of the fossil radio plasma through the shock wave. With a non-relativistic environment, and an ultra-relativistic fossil radio plasma gas equation of state, we find

$$C = \left(\frac{5M^2-1}{4}\right)^{\frac{3}{4}}, \quad (2)$$

where we assume that the shock has the same Mach number as 3C 129. This gives $C = 1.8$ for $M = 1.4$, and $C = 4.6$ for $M = 2.5$. Inserting this into Eq. 1, we find that that the fossil radio plasma has to be younger than $t_{\rm max} = 160$ Myr for $M = 1.4$ and $t_{\rm max} = 350$ Myr for $M = 2.5$. These maximal ages are estimated assuming an optimal initial field strength of $B = 2\mu$G, and would decrease for lower or higher field strengths. This estimate also neglects the increased electron cooling during the compression by the shock wave, or during earlier stages of the fossil radio plasma history (as discussed below). Therefore we expect the radio plasma to be significantly younger than $t_{\rm max}$.

4.3. Possible Origins for the Crosspiece Radio Plasma

The fact that the weak bow shock wave of 3C 129 could only have revived relatively young fossil radio plasma gives us a good chance to identify its origin, because the corresponding radio galaxy could still be active. There are two candidate sources in our 90cm radio map: 3C 129.1 and object C.

3C 129.1 resides at the cluster center. Its radio lobes should be highly buoyant in the cluster atmosphere, similar to those of M87 (Churazov et al. 2001). Such buoyant bubbles of former activity from 3C 129.1 are a possible explanation for sources A and B in our 327 MHz map. The faintness of these sources can be naturally understood as the effect of adiabatic expansion during the buoyant rise in the cluster atmosphere; using the derived spectral indices $\alpha \approx 2.4$, the synchrotron luminosity decreases by a factor $D^{-(2+4\alpha)/3} \approx D^{-3.87}$ due to volume expansion by a factor D.

The time required for radio lobe emission to travel from 3C 129.1 to the Crosspiece's position is $310\,{\rm Myr}/M_{\rm bubble}$, where $M_{\rm bubble} < 1$ is the Mach number of the buoyant bubble's rise. This is long compared with the maximal fossil radio plasma age, and probably too long to allow 3C 129.1 to be the Crosspiece's origin. Additionally, in such a scenario the maximal age of the radio plasma as calculated should also be significantly corrected downwards due to increased radiative cooling and adiabatic losses during the early (more compressed) stage of the rising bubble (see Enßlin & Gopal-Krishna (2001) for a formalism for detailed calculations of the spectra of aging and expanding radio plasma).

Source C as the origin of the Crosspiece's radio plasma would not have this difficulty, because it could have passed the present position of the Crosspiece relatively recently. The source itself is asymmetric with an elongation pointing directly towards the Crosspiece. Although it has a somewhat steeper than normal spectrum for an AGN ($\alpha \approx 1.5$), it is coincident with a known galaxy. Therefore we consider source C a more likely origin of the radio plasma revived by 3C 129's bow shock.

5. Conclusion

We present a 330 MHz ($\lambda \sim 90$ cm) radio map of 3C 129 and its companion 3C 129.1. In addition to the spectacular structure of this long NAT source, we also note a small perpendicular object near the head of the galaxy, which we call the Crosspiece. This object has a steep spectrum, and may be a fossil radio plasma revived by 3C 129's bow shock.

This is only one possible explanation for this feature, but it makes a couple of predictions which can be tested by future observations. First, the compression of a fossil radio plasma should align the magnetic fields with the shock surface. Because this surface is roughly perpendicular to the line of sight at its front edges, a relatively clear polarization signature should be visible (see Enßlin & Brüggen (2001) for numerical simulations of the radio polarization of shocked radio plasma). Second, if source C is the origin of the Crosspiece's radio plasma, there may be a low frequency trail connecting the two. During shock compression, the maximum frequency is shifted by only $C^{4/3} = 2.2...6.4$ (for $M = 1.4...2.3$, see the change of ν with C in Eq. 1 for $t_{\rm max}$ fixed), so a low surface brightness radio emission at and below 100 MHz is expected. Detailed radio spectra of the pre- and post-shock radio plasma would give an independent measurement of the shock compression and geometry in this case.

We note that if this scenario passes the proposed tests, it would help to disentangle the geometry of the infall of 3C 129 into the X-ray cluster, because the 3-dimensional velocity can be estimated from the structure of the Mach cone and the galaxies' redshifts. This would be an important step forward in our understanding of the peculiar morphology of 3C 129 in specific, and the nature of radio plasma in general.

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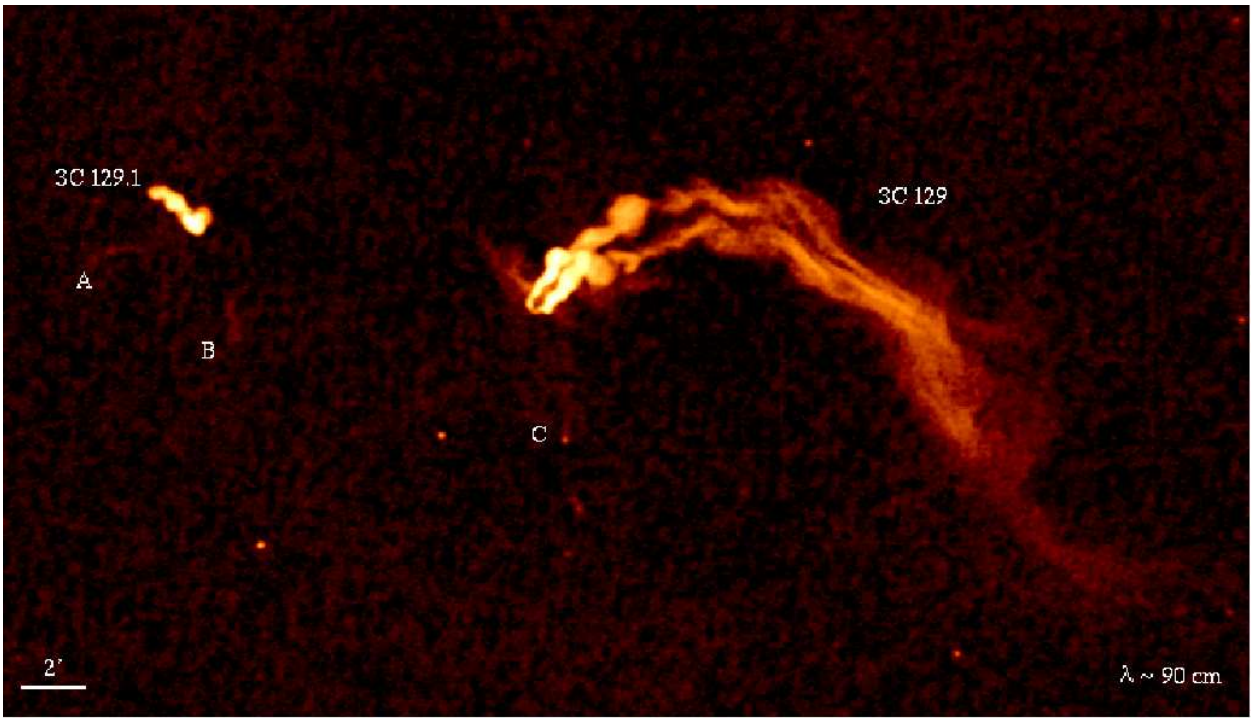

Fig. 1.— A wide-field image of 3C 129 and its companion 3C 129.1 at $\lambda \sim 90$ cm. The faint objects labeled A,B, and C have all been identified at other frequencies and are real. Note the small perpendicular extension to either side of 3C 129, which is the Crosspiece discussed in the text.

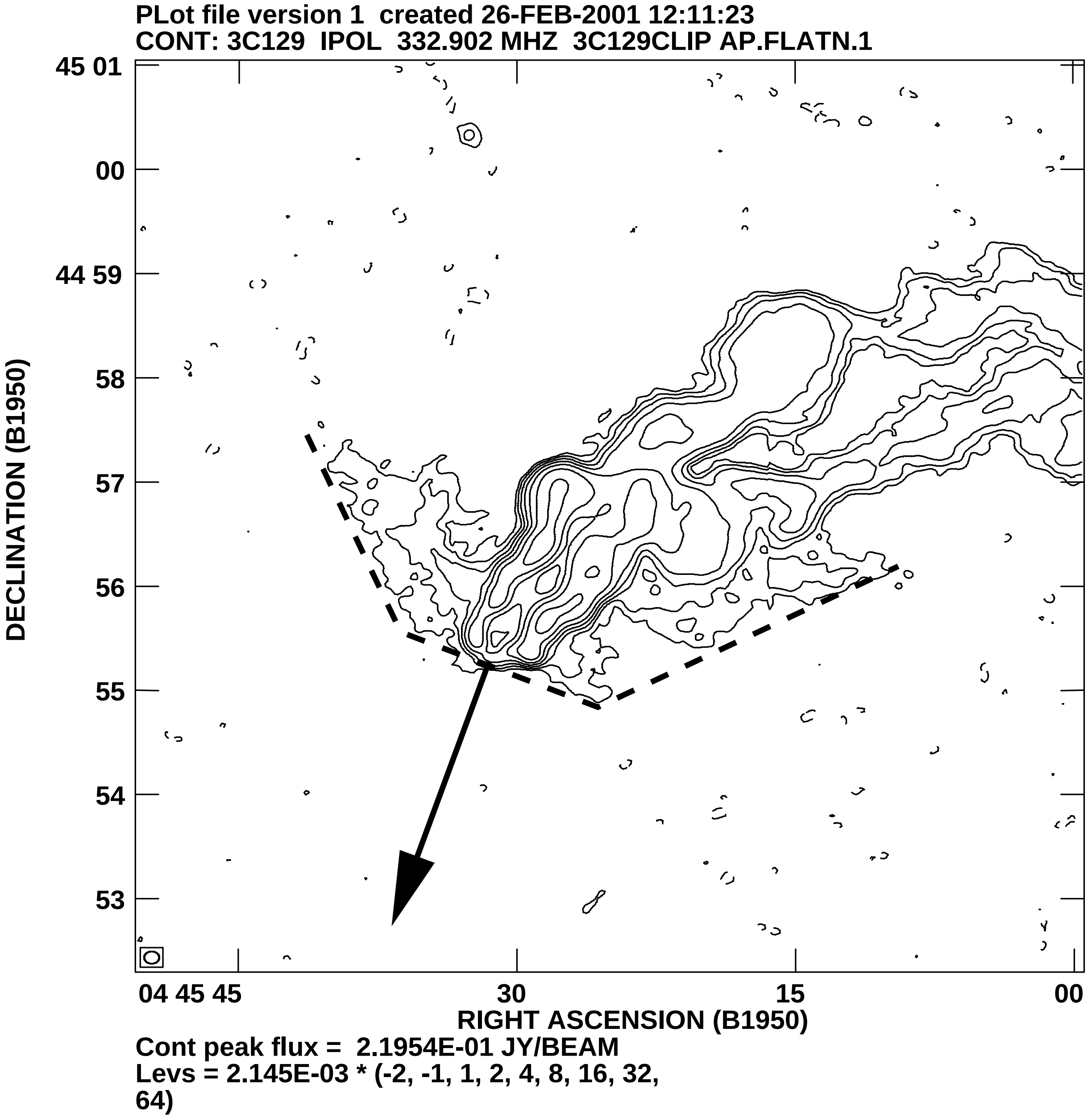

Fig. 2.— A closer look at the 90cm map near the head of 3C 129, showing the Crosspiece feature extending to both sides. Contour levels are multiples of the 3σ noise in the map. The dashed line sketches the suggested location of the shock wave, which would have a Mach cone opening angle of $\theta_{\rm Mach} \approx 90^{\circ}$. If this is correct, the arrow indicates the motion of 3C 129 within the plane of the sky. As argued in the text, the 3-dimensional motion should not differ more than $\sim 10^{\circ}$ from this. Note, that the radio trails of 3C 129 are likely buoyant in the cluster ICM, so that their orientation need not be exactly parallel to the galaxy motion. This is supported by the strong bending of the large scale morphology of the trails (Cowie & McKee 1975).