PKS 1510–089: A HEAD-ON VIEW OF A RELATIVISTIC JET

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ABSTRACT

The gamma-ray blazar PKS 1510–089 has a highly superluminal milli-arcsecond jet at a position angle (PA) of −28° and an arcsecond jet with an initial PA of 155°. With a ΔPA of 177° between the arcsecond and milli-arcsecond jets, PKS 1510–089 is perhaps the most highly misaligned radio jet ever observed and serves as a graphic example of projection effects in a highly beamed relativistic jet. Here we present the results of observations designed to bridge the gap between the milli-arcsecond and arcsecond scales. We find that a previously detected “counter-feature” to the arcsecond jet is directly fed by the milli-arcsecond jet. This feature is located 0.3″ from the core, corresponding to a de-projected distance of 30 kiloparsecs. The feature appears to be dominated by shocked emission and has an almost perfectly ordered magnetic field along its outside edge. We conclude that it is most likely a shocked bend, viewed end-on, where the jet crosses our line of sight to form the southern arcsecond jet. While the bend appears to be nearly 180° when viewed in projection, we estimate the intrinsic bending angle to be between 12° and 24°. The cause of the bend is uncertain; however, we favor a scenario where the jet is bent after it departs the galaxy, either by ram pressure due to winds in the intracluster medium or simply by the density gradient in the transition to the intergalactic medium.

Subject headings: galaxies: active — galaxies: jets — galaxies: kinematics and dynamics — quasars: individual: PKS 1510–089

1. INTRODUCTION

Extragalactic radio jets can change direction for a variety of reasons, such as deflections by massive clouds in the interstellar or intracluster medium, growth of hydrodynamical instabilities, or precession at the base of the jet. Core dominated radio sources are oriented with their jets pointed nearly along our line of sight, greatly exaggerating in projection any intrinsic trajectory changes. Small intrinsic changes can therefore appear as large angle misalignments between the jet axes observed on parsec and kiloparsec scales. Indeed, large angle misalignments have been observed in some core dominated radio sources (e.g. 3C 309.1, Wilkinson et al. 1986), and the distribution of jet misalignment angles has been extensively studied (e.g. Pearson & Readhead 1988; Wehrle et al. 1992; Conway & Murphy 1993; Appl, Sol, & Vicente 1996). While the distribution is known to have a bimodal shape, with a main peak of misalignment angles near 0° and a secondary peak near 90° (Pearson & Readhead 1988; Conway & Murphy 1993), misalignment angles larger than 120° are quite rare. Between two recent studies by Tingay, Murphy, & Edwards (1998) of southern EGRET sources and by Lister, Tingay, & Preston (2001) of the Pearson-Readhead sample, the misalignment angles of fifty sources are compiled; just two of those sources have misalignment angles greater than 120°, and not one is misaligned more than 150°.

Here we discuss the highly misaligned radio jet of PKS 1510–089 (z = 0.360), a radio selected, high polarization quasar (Hewitt & Burbidge 1993; Stockman, Moore, & Angel 1984). PKS 1510–089 has been detected in γ-rays by EGRET (Hartman et al. 1999) and exhibits apparent jet motions in excess of 20 times the speed of light (Homan et al. 2001; Wardle et al. 2002). Superluminal motion is a natural consequence of a highly relativistic jet pointed nearly right at us (Rees 1966; Blandford & Königl 1979), leading to a compression of the observed time scale and magnifying intrinsic pattern speeds: β_{app} = β sin θ/(1 − β cos θ) where β_{app} is the observed speed, β is the intrinsic pattern speed, and θ is the angle between the jet axis and the line of sight. If traveling at the optimum angle for superluminal motion, β = cos θ, the parsec-scale jet of PKS 1510−089, at an apparent speed of 20c, lies within just three degrees of our line of sight.

O’Dea, Barvainis, & Challis (1988) mapped the arcsecond scale structure of PKS 1510−089 at 5, 15 and 22 GHz using the Very Large Array (VLA). They observed a jet extending nine arcseconds to the south-southeast at 5 GHz and an oppositely directed counter-feature at just 0.3 arcseconds at the higher frequencies. Three epochs of early Very Long Baseline Interferometry (VLBI) observations at 1.7 GHz (summarized in Bondi et al. 1996) appeared to show the milli-arcsecond scale jet directed toward the southern VLA jet. On the basis of these results, PKS 1510−089 has been considered a well aligned source in studies of misalignment angles in gamma-ray blazars (Tingay et al. 1998; Hong, Jiang, & Shen 1998; Cao 2000).

More recent Very Long Baseline Array (VLBA) observations ranging from 2 GHz up to 43 GHz (Fey & Charlot 1997; Kellermann et al. 1998; Homan et al. 2001; Jorstad et al. 2001; Wardle et al. 2002) show the jet extending up to 40 milli-arcseconds (at 2 GHz) to the north-northwest, directly toward the “counter-feature” at 0.3″ observed by O’Dea et al. (1988). These more...
recent and more sensitive observations (as well as the deep 1.7 GHz observations presented here) show no sign of a southern milli-arcsecond jet, suggesting that the early VLBI results may have simply mis-identified the core.

With a highly superluminal milli-arcsecond jet extending to the north-northeast, a bright VLA feature directly in its path at 0.3", and an arcsecond VLA jet oppositely directed by \(\sim 180^\circ\), the connection between the jets on these scales is an intriguing puzzle. Here we report the results of observations designed to fill the gap in resolution between the previous VLBI and VLA observations of this source. The observations are described in §2, and in §3 we suggest and analyze two general models to explain the jet trajectory of this highly superluminal blazar. Throughout this paper we assume a cosmology with \(H_0 = 70 \text{ km} \, \text{s}^{-1} \, \text{Mpc}^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\), and we choose a spectral index convention: \(S_{\nu} \propto \nu^{\alpha}\).

2. OBSERVATIONS AND RESULTS

On August 11, 2001 we made deep VLBI observations of PKS 1510–089 using the National Radio Astronomy Observatory’s (NRAO) VLBA plus a single VLA antenna (VLBA+Y1) at 1.7 and 5.0 GHz. The observations were taken in dual-polarization mode so that we could study the linear polarization of the jet as a probe of the underlying magnetic field structure. The data were correlated on the VLBA correlator and were processed with NRAO’s Astronomical Imaging Processing System, AIPS, (Brindle & Greisen 1994; Greisen 1988) and the Caltech DIFMAP package (Shepherd, Pearson, & Taylor 1994, 1995) using standard techniques for VLBI polarization observations (e.g. Cotton 1993; Roberts, Wardle, & Brown 1994). The feed leakage terms were corrected using the strong, unpolarized source OQ208.

Figure 1 displays our naturally weighted and tapered images of PKS 1510–089 at 1.7 GHz. The tapered image was made using a Gaussian weight taper in the (u,v)-plane with a weight factor of 0.3 at a radius of 10 MA. The images show a strong core with a jet extending to the north-northeast for approximately 150 milli-arcseconds (mas) before fading. The strong “counter-feature” seen by O’Dea et al. (1988) is a prominent feature in both the naturally weighted and tapered maps. We do not present polarization maps of our 5 GHz data here, although an intensity map of the milli-arcsecond jet is included as part of figure 2. We note that, with three times the resolution of the 1.7 GHz images, the 5 GHz images resolve out most of the extended emission. We do make use of the 5 GHz data to measure the spectral index of the milli-arcsecond scale jet.

Figure 2 is a multi-frame figure showing the jet from arcsecond to milli-arcsecond scales. The first frame (left) is a reprocessed version of the 5 GHz VLA image obtained by O’Dea et al. (1988). The second frame (center) is our tapered 1.7 GHz VLBA image with a wider field of view to show that there is no hint of jet emission to the south. The third frame (right) is our naturally weighted 5 GHz VLBA image of the milli-arcsecond jet.

2.1. The Feature at 0.3"

At first glance the feature appears to be almost circular in shape, approximately 100 mas in diameter (\(\sim 500 \text{ parsecs at } z = 0.360\)). The interior of the feature has a sloping brightness profile that increases toward the outside edge. The outside edge itself is defined by a sharp brightness gradient and is distinctly curved, almost semi-circular in shape. The edge toward the core is less bright and is not clearly defined.

The feature is strongly polarized in a narrowly confined region along part of its outside edge. Here the fractional polarization climbs well above 50%, and it approaches the theoretical maximum for synchrotron radiation (71% for \(\alpha = -0.6\)). Indeed, at the very outside edge of the feature, the theoretical maximum appears to be exceeded in places; however, polarization and intensity levels have sharp gradients there, and uncertainty in the resulting fractional polarization can be large. Based on the noise levels in our tapered maps, we can say that the polarization at the very outside edge exceeds 65% at the 95% confidence level. The magnetic field must be almost perfectly ordered (as viewed in projection) at this point to explain such high levels of polarization. This provides an important constraint on models for this feature.

The polarization vectors in the map have been corrected for the integrated rotation measure of \(\pm 15 \pm 1 \text{ rad/m}^2\) (Simard-Normandin, Kronberg, & Button 1984) which rotates the electric vectors by 28\(^\circ\) at this frequency. The resulting polarization angles in this feature agree well with those measured by O’Dea et al. (1988) at 15 GHz. The intrinsic polarization vectors are very nearly perpendicular to the curved outside edge of the feature. The projected magnetic field (90\(^\circ\) to the polarization vectors) is therefore parallel to and curving around the outside edge of the feature.

O’Dea et al. (1988) measure an integrated spectral index for the 0.3" feature of \(\alpha \sim -0.6\) between the closely spaced frequencies of 15 and 22 GHz, and they note that its integrated flux is 26 mJy at 22 GHz. Comparing to our integrated flux of 0.13 Jy at 1.7 GHz, we find the spectral index to indeed be \(\alpha = -0.6 \pm 0.1\) over more than a decade in frequency. At \(-0.6\), the spectral index of the feature is less steep than the milli-arcsecond scale jet for which Homan et al. (2002) find \(\alpha = -0.9 \pm 0.1\) from multi-epoch VLBA observations at 15 and 22 GHz. Fitting simple models to our 1.7 and 5 GHz data, we find a spectral index further out (\(R \sim 20 - 30 \text{ mas}\)) in the milli-arcsecond jet of \(\alpha = -0.8 \pm 0.1\).

3. DISCUSSION

From figure 1, there seems to be little doubt that the 0.3" feature is fed directly by the milli-arcsecond jet. In this section we explore the nature of this feature and its relation to the milli-arcsecond and arcsecond scale jets.

3.1. The Milli-Arcsecond Scale Jet

Due to its very high proper motion, we know the axis of the milli-arcsecond jet makes a small angle with our line of sight. For the purposes of this discussion we take this alignment angle, \(\theta_{V_{\text{LBA}}}\), to be 3\(^\circ\), which is the optimum angle for the superluminal motion of 20c observed by Homan et al. (2001).

The motion in the milli-arcsecond jet appears to be straight along a structural position angle of \(-28^\circ\) (Homan et al. 2001). This motion points directly at the apex of the 0.3" feature which also has a structural position angle of \(-28^\circ\). However, the path of the jet from a couple milli-arcseconds to 0.3" is not entirely straight, and we note that the third panel in figure 2 shows the jet ridge-line to wiggle in the plane of the sky after the first 10 mas. The jet ridge-line is defined by the bright parts of the jet and small wiggles in it will be greatly magnified by the projection effects of a 3" viewing angle. The larger scale images in figure 1 show the ridge-line of the jet to be essentially straight but slightly south of the \(-28^\circ\) position angle of the 0.3" fea-
F. I. G. 1.— Naturally weighted (above, panel (a)) and tapered (below, panel (b)) VLBA+Y1 images of PKS 1510−089 at 1.7 GHz. The left image is total intensity contours ($\times \sqrt{2}$ steps), the center image is polarized intensity contours ($\times \sqrt{2}$ steps) with the electric vector directions indicated by tick-marks, and the right image is total intensity contours ($\times 2$ steps) superimposed with grayscale fractional polarization. The lowest contour levels are 0.5 mJy/beam in panel (a) and 1.0 mJy/beam in panel (b). The FWHM sizes of the elliptical Gaussian restoring beams are indicated by the stick figures in the upper left hand corners of the panels.
ture, perhaps indicating that the jet feeds the southwest edge of the 0.3″ feature. However, it is important to remember that the ridge-line may not trace the main flow, and the milli-arcsecond jet could be quite broad (and largely too dim to be seen), possibly filling the entire angle subtended by the 0.3″ feature.

While the wiggles of the jet ridge-line likely represent very small bends magnified by projection, we have no information about whether the jet bends toward or away from the line of sight by a significant amount. In the absence of better information, we will make the simple assumption that the jet path from milli-arcsecond scales to 0.3″ is essentially straight and that the position of the 0.3″ feature is projected by the same 3° angle as the proper motion. This would place the 0.3″ feature at a de-projected distance of 30 kiloparsecs (kpc) from the nucleus. Given the 500 pc transverse size of the feature, the intrinsic full-opening angle of the milli-arcsecond jet must be \( \lesssim 1° \).

3.2. The Arcsecond Scale Jet

The bright arcsecond jet is \( \simeq 9″ \) long at a structural position angle of 160°. The inner part of the arcsecond jet is at a position angle of \( \simeq 155° \) (O’Dea et al. 1988), placing it very nearly 180° from the direction of the milli-arcsecond jet.

It is interesting that the inner part of the arcsecond jet (1″ → 3″), although apparently straight, does not form a line that extrapolates directly back to the core. This suggests that the arcsecond jet has been bent somewhere from its origin to the point where it is visible in the VLA map.

Another interesting feature of the VLA map is that there is no clear sign of the counter-lobe. The counter-jet, of course, is highly beamed away from us; however, we might expect to see the unbeamed emission from the counter-lobe. In one of the models presented below, the approaching jet bends directly across our line of sight, forming the apparent 180° misalignment between the milli-arcsecond and arcsecond jets. In this bent jet model, the counter-lobe would lie directly behind the approaching arcsecond jet, and we perhaps see evidence for this at radii 4″ → 6″ in the 5 GHz VLA image from figure 2. There is significant excess, fluffy emission in this region which does not appear to be directly associated with the main flow of the jet. This may be emission from the hidden counter-lobe which has been eclipsed by the bent approaching jet.

3.3. The Feature at 0.3″

The feature appears to be dominated by shocked emission. It has approximately one hundred times the surface brightness a straight continuation of the jet would have at this radius. Doppler boosting can give at most a factor of six in brightness if the jet has turned directly toward us at this point. If the jet has decelerated much from the \( \gamma \simeq 20 \) flow at its base, any gain from Doppler boosting would be much less. Thus shock-enhanced emission and/or very long path lengths are necessary to explain the brightness. The feature also has a spectral index which is less steep than observed in the milli-arcsecond jet, suggesting a locally re-accelerated particle population. The very high fractional polarization of the feature, oriented transverse to the jet direction, is also consistent with a shock, although we note that one possible model (described below) would allow the polarization to be produced through shear.

We estimated the jet brightness at 0.3″ by taking various 1-D slices through the images and extrapolating the power-law decay of jet brightness with radius.
Two natural models for the feature are

- **A terminal bow shock in the milli-arcsecond jet.** In this model the arcsecond jet is an older jet and is not related to the milli-arcsecond jet. The jet direction may have changed either in a discrete way due to an event that profoundly changed the black hole/accretion disk system or in a more continuous fashion due to some kind of precession. Any precession model would have to explain the existence of the apparent “preferred” jet direction of the arcsecond jet.

- **A shocked bend in the jet.** Here the jet bends almost directly across our line of sight, and the arcsecond jet is simply the continuation of the jet after the bend.

The very high levels of fractional polarization would seem to rule out a simple bow shock model. Given the close alignment between the jet and the line of sight, we would expect to view the bow shock nearly end-on, so the projected magnetic field would appear almost completely tangled, giving little, if any, net polarization. For the very high levels of fractional polarization that we see, we would have to view the bow shock from the side (e.g., Laing 1980). Relativistic aberration which can change viewing angles considerably for highly relativistic flow is of little help here because the bow shock advance speed is likely be quite slow.

In the second model, where the 0.3\arcsec feature marks a shocked bend in the jet, the jet is assumed to cross our line of sight at this point and continues (unseen in our image due to low surface brightness) to form the arcsecond scale jet. Figure 3 depicts a cartoon of this model. The jet can be either (1) a wide jet which crosses our line of sight directly so that we see the cylindrical cross-section of the jet, or (2) a somewhat narrower jet which crosses our line of sight so that the plane formed by the bend does not quite contain the line of sight. In the second case, the 0.3\arcsec feature is formed by the doubled over projection of the bent jet, with the jet entering the bend at the southwestern corner and departing on a parallel (but reversed) track from the northeastern corner. The high levels of polarization can be directly due to compression from a shock at the bend and/or due to shearing of the magnetic field around the bend. For shear to have a significant contribution, our line of sight must be out of the plane of the bend (case 2, above) by at least a small amount.

### 3.4. A Bent Jet

We favor the ‘simple’ bent jet explanation which ties together the milli-arcsecond jet, the shocked feature at 0.3\arcsec, and the arcsecond scale jet. Here we explore this model in more detail.

#### 3.4.1. The Magnetic Field Order

If the magnetic field order is produced entirely by a shock at the bend, then to observe the \( \gtrsim 65\% \) linear polarization, the field must be almost perfectly ordered at that point which requires a very strong shock (e.g. Hughes, Aller & Aller 1985). Strongly shocked emission is greatly enhanced in intensity, and this is consistent with the high surface brightness of the feature; however, the profiles of the intensity and polarization seem inconsistent with a simple shock model. Figure 4 shows a one dimensional slice through our tapered 1.7 GHz image taken along a position angle of \(-28^\circ\) from the VLBI core through the apex of the feature at 300+ milli-arcseconds. The polarization occurs at the very outside of the feature; however, the intensity peaks further back from the outside edge and falls off relatively slowly across the width of the feature.

In a simple compression shock, the intensity and polarization enhancement would be expected to coincide (e.g. Hughes et al. 1985). Here the polarization enhancement (as seen from our viewing angle) appears confined to the very outside of the bend. It seems possible that aberration in a highly relativistic flow could distort viewing angles enough before and after the bend to confine the high polarization to the very outside edge where the range of viewing angles is the narrowest; however, simple models we created with streaming flow around a semi-circular bend do not have the polarization falling off fast enough from the outside edge. These simple models considered only the wide jet case, where the plane of the bend includes the line of sight. More complex bends, where the line of sight does not include the plane of the bend will have greater possibilities (including a wider range of superposition effects) for reducing the projected field order away from the outside of the bend.

If the field order is produced entirely by a very strong shock, we must be viewing the shock plane nearly edge-on to see \( \gtrsim 65\% \) polarization. For a localized shock, this requires another fortunate coincidence of viewing angles in a source which is already unusual. If the shock is spread out along the bend to some degree, the necessary coincidence in viewing angles is lessened; however, it is difficult to imagine a very strong shock being spread out in such a fashion.

If the jet is somewhat narrower than the 0.3\arcsec feature and the line of sight does not include the plane of the bend, then at least some (and perhaps most) of the magnetic field order can be produced through shear. Shear will stretch the magnetic field lines along the jet. At the apex of the bend (as viewed in projection) the local jet direction is perpendicular to that in the milli-arcsecond jet; therefore, any sheared field would also appear perpendicular to the milli-arcsecond jet. The sheared field should appear to curve around the apex of the bend, and this is precisely what we observe. One concern is that we might expect to see polarization along more of the feature as shear would be occurring along the entire length of the bend; however, it is only near the apex of the projected bend that we see the magnetic field order undiluted by superpositions with other parts of the jet. We note that even with shear producing (at least some of) the observed magnetic field order, we still need shocked emission in the bend to explain the intensity enhancement and spectral index.

#### 3.4.2. The Bending Angle

While forming a bend nearly 180\degree in projection, the intrinsic bending angle could be quite small. The close alignment of the jet with the line of sight magnifies not only intrinsic bends, but also the apparent opening angle of the jet, \( \phi_{\text{obs}} = \phi / \sin \theta \) where \( \theta \) is the angle the jet makes with the line of sight. As shown in section 3.1, before the bend the intrinsic full-opening angle of the jet was \( \phi \lesssim 1^\circ \). The jet’s intrinsic opening angle may change in the bend, perhaps flaring outward due to a reduction in Mach number (Mendoza & Longair 2002), and we parameterize the intrinsic opening angle after the bend to be \( \lesssim 1^\circ \) degrees. The apparent opening angle after the bend is \( \phi_{\text{obs}} \gtrsim 10^\circ \) from the size of the knot at 2.6\arcsec. Taken together, the intrinsic and observed opening angles give a jet angle to the line of sight after the bend of \( \theta_{\text{VLA}} = \phi / \phi_{\text{obs}} \lesssim 6\eta \) degrees.

We can get an independent constraint on \( \theta_{\text{VLA}} \) from the de-
FIG. 3.—Cartoon model for the bent jet geometry. $D$ is the diameter of the jet, and $R$ is the radius of curvature of the bend. Two possible “end-on” views at the point of the bend are depicted superimposed on our naturally weighted image of the $0.3\arcsec$ feature with polarization vectors over-plotted. The first is the cross-section of a wide jet pointed directly along our line of sight. The second is of a narrower jet that is not quite directly along our line of sight, so that it appears to double-over at the bend. In this second case, the plane of the jet, as defined by its two “straight” pieces on either side of the bend, does not quite contain the line of sight.
projected size of the 9″ jet, which in projection appears just 45 kpc long. In their study of Doppler beaming in large scale jets, Wardle & Aaron (1997) place a rough upper limit on the size distributions of quasar jets corresponding to a single-sided jet length of 420 kpc if the parent population for quasars cuts off at a viewing angle limit of 60°. In a similar study, Hardcastle et al. (1999) find that a normal distribution fits their data well with a central value corresponding to a single-sided jet length of 210 kpc and a standard deviation of 85 kpc.3 Taken together, these values require θ_vla > 6° with a reasonable range between 9° and 21° to the line of sight. Given that the milli-arcsecond jet is at an angle of 3°, we estimate the intrinsic bending angle is between 12° and 24°.

3.4.3. What Caused the Bend?

As noted in §3.1, the bend lies at a de-projected distance of 30 kpc from the central engine. Optically, PKS 1510–089 is dominated by a strong point source (Hutchings, Crampton, & Campbell 1984), and the size of its host galaxy has not yet been determined (Kotilainen, Falomo, & Scarpa 1998). Given the typical scale size of the elliptical hosts of radio galaxies, ≃ 30 kpc (Taylor et al. 1996), the bend likely lies near the boundary of the host galaxy. The jet could be bent by an interaction with a massive cloud, ram pressure from winds in the intracluster medium, or simply the density gradient between the interstellar and intergalactic medium if the gradient is non-uniform or if the jet crosses it at an oblique angle (P. Hughes, private communication). Discriminating between these possibilities is difficult; however, whatever the cause, the bend must be stable on the ~ 10^7 yr timescale necessary to form the southern arcsecond jet.

Hydrodynamical simulations show that jet-cloud interactions usually end with the disruption of either the cloud or the jet (e.g. De Young 1991), and only relatively dense, slow jets are capable of producing fairly long lived bends via jet-cloud collisions (Wang, Witta, & Hooda 2000). Wardle et al. (2002) present evidence that PKS 1510–089 has a light jet with a particle population dominated by electron-positron pairs. Combined with the highly relativistic nature of the milli-arcsecond jet and the location of the bend near the probable boundary of the host galaxy, we consider it more likely that the jet is bent after it leaves the galaxy, either by ram pressure from winds in the intracluster medium or by the density gradient in the transition to the intergalactic medium.

4. CONCLUSIONS

We find that the apparent ≃ 180° misalignment between the milli-arcsecond and arcsecond radio jets in PKS 1510–089 is most likely due to a small angle intrinsic bend of ≃ 12°–24°, viewed in projection. Our new images show the highly superluminal VLBI jet to point directly at and nearly connect with a previously detected “counter-feature” to the arcsecond jet, leaving little doubt that this feature at 0.3″ is actually part of the approaching jet. We imaged the feature in detail and find it to be dominated by shock enhanced emission and to have very high levels of polarization confined along its outside edge. The projected magnetic field must be almost perfectly ordered at this point, ruling out a simple bow-shock model where the 0.3″ feature marks the terminal spot in the VLBI jet. Instead, we prefer

3 The values from both the Wardle & Aaron (1997) and Hardcastle et al. (1999) papers have been converted to our choice of cosmology.
a shocked-bend model where the jet bends across our line of sight at this point, creating highly ordered magnetic field either as a direct consequence of the shock itself or through shear. The bend occurs at a de-projected distance of $\sim 30$ kiloparsecs from the nucleus, near the probable boundary of the host galaxy. The cause of the bend is uncertain; however, we favor a scenario where the jet is bent after it departs the galaxy, either by ram pressure from winds in the intracluster medium or by the density gradient in the transition to the intergalactic medium.

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