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DISCOVERY OF THE BOW SHOCK OF CYGNUS A

C. L. CARILLI
Department of Physics, Massachusetts Institute of Technology; and National Radio Astronomy Observatory[1]
R. A. PERLEY
National Radio Astronomy Observatory
AND
J. H. DREHER
Department of Physics, Massachusetts Institute of Technology
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ABSTRACT

Rotation measure images of Cygnus A indicate that a bow shock precedes the supersonic advance of hot spot B into the intergalactic medium. The shock is radio quiet and is observed only by the rotation measure discontinuity which occurs at the point where the fields and particles in the IGM are compressed by the shock. The fact that this discontinuity is projected onto part of the source provides information on the three-dimensional structure of the radio source and supports models of extragalactic radio sources in which the jet varies direction on relatively short time scales. From the observed rotation measures, we calculate magnetic field strengths in the cluster gas of $\sim 7.5\ \mu$G.

Subject headings: galaxies: intergalactic medium — galaxies: jets — shock waves — radio sources: galaxies

I. INTRODUCTION

High-luminosity double radio sources generally show radio "hot spots" near the ends of the lobes. A hot spot is considered to be the "working surface" where the jet, which powers the source, terminates upon impact with the intergalactic medium (cf. Begelman, Blandford, and Rees 1984). Theoretical and numerical studies suggest that at this point two shocks are formed, a beam and a bow shock (cf. Blandford and Rees 1974; Norman *et al.* 1982). The beam shock decelerates the supersonic jet, converting much of the bulk kinetic energy of the jet into thermal and relativistic particle energies. The bow shock propagates into the undisturbed intergalactic medium (IGM) and compresses, heats, and accelerates the static external gas. The two shocked fluids (jet and IGM) then meet subsonically along a contact discontinuity, where pressure gradients turn the jet material back into the lobes. It has generally been assumed that the radio emission is from shocked jet material inside the contact discontinuity—leading to a picture of a radio-emitting lobe of waste jet material, enveloping the jet (e.g., Williams 1985) and in turn surrounded by a radio-quiet "sheath" of high-pressure shocked IGM. However, the possibility has also been raised (e.g., Rudnick 1988) that the bow shock as well as the beam shock might accelerate relativistic electrons and, thus, that the sheath itself might contribute to the radio emission. We present direct evidence that this is not the case in Cygnus A.

A modification of this model is the hypothesis that jets alter direction on time scales short compared to source lifetimes (Scheuer 1982). This is supported by the facts that jets are not always straight from the core to the hot spot, that hot spots are often recessed from the leading edge of the radio lobe, and that observed lobes are often much wider than are produced by numerical simulations of fixed-axis jets. In this picture, after the jet changes direction a new hot spot is formed where the jet impinges obliquely on the side wall of the radio lobe, while the old hot spot quickly fades into the background lobe. The new, "primary" hot spot creates an indentation in the lobe's side wall, inducing a strong bow shock in the external gas as it extends and widens the lobe in this new direction. Central to this idea is that hot spots are essentially transient features: the time scales for both adiabatic expansion and synchrotron losses for the Cygnus A hot spots are $\leq 10^5$ yr, while the age of the source is $\geq 3 \times 10^6$ yr (Winter *et al.* 1984). Motivated by the observation that radio sources often show two hot spots in each lobe (Laing 1982), Williams and Gull (1985) have further elaborated Scheuer's idea by proposing that the outflow from the primary hot spot might remain well enough collimated (or recollimate) to form a secondary hot spot where the outflow hits an opposing wall of the lobe. Observations of the detailed structure of the Cygnus A hot spots seem consistent with this picture (Carilli, Dreher, and Perley 1988).

Although the radio-quiet bow shock and sheath play an important role in the physics of extragalactic radio sources, they have, as yet, never been detected. In this *Letter*, we present evidence for the bow shock associated with the B hot spot in Cygnus A. The shock shows up through its contribution to the Faraday rotation of the polarized emission from the radio source. The difficulty with this method of detection is trying to separate the effect of the shocked gas from the effect of the large-scale gas distribution in the cluster. However, if the source geometry is such that the bow shock actually projects transversely onto part of the lobe, then at this point one would expect a discontinuous increase in rotation measure due to the compression by the shock of the particles and tangential magnetic fields. Such a geometry might not be uncommon if the hot spot is situated along the side wall of the radio lobe, as in the Scheuer model. This phenomenon seems to occur in Cygnus A.

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II. CYGNUS A AND ROTATION MEASURES

Cygnus A is the best studied of the double radio sources and has served as the archetype for those sources which display radio hot spots near the ends of the lobes (cf. Hargrave and Ryle 1974; Alexander, Brown, and Scott 1984). The distance to the source is 230 Mpc,[2] which makes it one of the closest powerful radio galaxies (Spinrad and Stauffer 1982). The source is associated with a large, cD type galaxy, and is situated at the center of a dense, X-ray–emitting, "cooling flow" cluster gas, with a mass infall rate $\geq 120\ M_{\odot}\ \mathrm{yr}^{-1}$ (Arnaud *et al.* 1987). The radio source extends ~ 60 kpc from the associated galaxy center.

Multifrequency polarimetric radio observations obtained with the VLA have revealed that Cygnus A lies behind a deep "Faraday screen," with extremely large rotation measures (RM) and RM gradients (Dreher, Carilli, and Perley 1987, hereafter DCP). We pointed out that the most physically reasonable candidate for this Faraday screen is the dense X-ray–emitting cluster gas known to surround the radio source. However, the question of whether the observed rotation measure is caused by the overall cluster gas distribution ($r_{\mathrm{core}} \sim 130$ kpc; Fabbiano *et al.* 1979), or by the sheath of shocked gas immediately surrounding the lobes (scale $\sim$ few kpc) remained unresolved. The principal problems, in both cases, were the large magnetic fields required (≥ 5 and 50 μG, respectively), and the origin of the large-scale order in these fields.

[2] We assume $H_0 = 75\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, which gives a scale of $1'' \sim 1$ kpc, at the source.

III. THE FARADAY SCREEN IN THE NORTHWEST LOBE

The RM distribution in the vicinity of the hot spots at the end of the northwest lobe is shown in Figure 1 (Plate L22). While overall the values are large and seem to be independent of total intensity, there is a curious "hemispherical" structure of large RM, nearly concentric with the compact hot spot B. Rotation measures rise gradually from near zero in the feature's interior up to over 1000 rad m^{-2} at a distance of ~ 3 kpc north and west of the hot spot, and then fall abruptly back toward zero further out.[3] *A sharp discontinuity in RM such as this is exactly what one would expect at the location of a compressional bow shock preceding the supersonic advance of hot spot B into the IGM.* The jet enters the lobe to the southeast, and seems to be directed toward the compact hot spot B (Carilli, Dreher, and Perley 1988).

In Figure 2 we present a model for a three-dimensional source structure which would give rise to the observed RM distribution. The observers are located at the lower right. The geometry in the third dimension is dictated by the fact that, since the observed rotation is caused by gas in front of the radio-emitting regions (DCP), hot spot B must lie on the edge of the radio lobe closest to us. This allows the discontinuous increase of densities and tangential fields caused by the associated bow shock, and the corresponding change in rotation measures, to project transversely onto the lobe some distance ahead of the hot spot. Note that there is no feature in the radio continuum emission corresponding to the sheath despite the high dynamic range of our maps; thus the sheath must contribute little or nothing to the radio emission of the lobes.

[3] Pixels along the edge of the feature were blanked due to depolarization caused by large RM gradients.

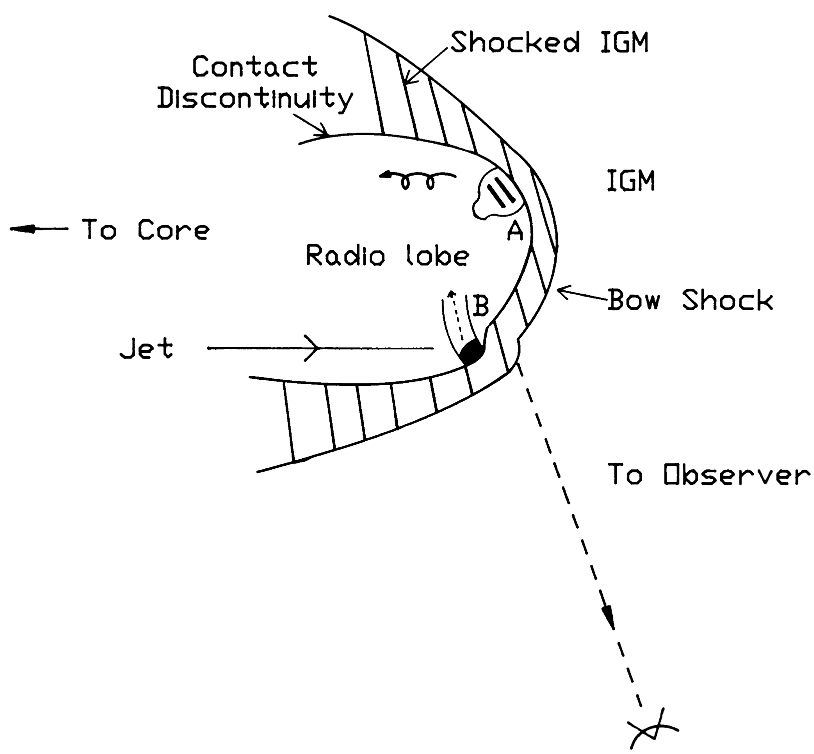

FIG. 2.—A schematic diagram of the implied three-dimensional geometry from the observed RM distribution. Hot spots A and B are labeled, along with some of the other important hydrodynamic features. In this view, the observer is to the lower right. Hence, the discontinuous change in RM caused by the compressed fields and particles along the bow shock associated with hot spot B will project transversely onto the front of the lobe.

The magnitude of the intergalactic magnetic fields can be calculated from the observed RM, given the electron density and a geometry (see eq. [A5] in DCP). The line-of-sight distance can be assumed roughly to be the standoff distance, ~ 3 kpc. The density can be determined assuming adiabatic shock jump conditions (under reasonable assumptions, the X-ray cooling time is $\sim 10^9$ yr for the shocked gas, which is two orders of magnitude longer than the source age), and using densities in the undisturbed IGM determined from X-ray observations (Arnaud *et al.* 1984, as rescaled in DCP). The Mach number of the shock is set by the ratio of internal ($P_{\rm hs}$) to external (P_x) pressures.[4] Minimum energy calculations yield hot spot pressures of $P_{\rm hs} \geq 5 \times 10^{-9}$ dynes cm^{-2}, while external X-ray emitting gas pressures are lower by a factor ~ 60 (using a temperature of 4.1 keV; Arnaud *et al.* 1987). This implies a minimum Mach number for the advancing hot spot of $M_{\rm hs} = 7$, and a compression ratio of 3.8. Hence, the electron densities behind the bow shock are ~ 0.025 cm^{-3}. Assuming no field reversals along the line of sight, and given RM values of 1000 rad m^{-2} along the shock, we calculate a required line-of-sight magnetic field of 16.5 μG in the shocked gas (any reversal of field direction will increase this estimate). If these fields are simply shock-compressed external fields, then the tangential field strengths in the external gas must be about 4.3 μG, which implies cluster fields of about 7.5 μG, if the distribution is isotropic.

A second potentially useful parameter is the observed standoff distance, $l_{\rm so}$. For a strong adiabatic shock, $l_{\rm so}$ is essentially set by continuity and is relatively insensitive to Mach number. For instance, a sphere of radius r in a hypersonic flow will create a bow shock at a standoff distance, $l_{\rm so} \sim r/[2(5)^{1/2}]$. This naive model would imply a standoff distance of about 0.2 kpc in Cygnus A if r is set by the hot spot radius—well below the observed value of 3 kpc. Three factors are probably responsible for the larger observed standoff distance. First, the hot spot is not a rigid object but a complex flow feature, with material both flowing into and out of the hot spot. Axisymmetric studies of light, hypersonic jets by Norman, Winkler, and Smarr (1982) seem to indicate a standoff distance 1–2 times the hot spot diameter. This is still somewhat smaller than that observed. Second, in our model the primary hot spot forms against a preexisting sheath of IGM, which will perturb the flow until the new hot spot completely dominates the hydrodynamics of the lobe. Interestingly, the numerical simulations of Williams and Gull (1985) for this situation, despite very limited numerical resolution, yield a standoff distance roughly consistent with that observed. In particular, it appears that the standoff distance is set more by the size of the lobe than of the hotspot, with $l_{\rm so}$ about one-fourth the lobe radius. This is consistent with the simple continuity arguments above, but with r = lobe radius (which is not unexpected, since material must flow around the lobe as well as the hot spot). Last, changing viewing angle can only increase the projected standoff distance over its minimum value.

IV. DISCUSSION AND SUMMARY

a) *Source Dynamics*

First, observation of the bow shock preceding the hot spot advance into the IGM is strong evidence in support of the basic double-shock structure model for the jet working surface. Second, we see that, at least in this source, the radio emission seems to be from material inside the contact discontinuity. Last, the inferred three-dimensional geometry necessitates a compact hot spot which lies along a side wall of the radio lobe, and not at the very end of the lobe. This is consistent with models of radio jets which alter their direction on time scales short compared with source lifetimes (Scheuer 1982; Williams and Gull 1985). Our observations are not consistent with other models (e.g., Kronberg and Jones 1982) that invoke various instabilities in the backflow to explain recessed hot spots, since these instabilities would not be expected to generate bow shocks.

b) *Faraday Screen*

From the observed RM distribution, we now know that up to 1000 rad m^{-2} of the Faraday screen associated with the source can be caused by the sheath of shocked gas around the lobe. We also know that if the observed RM discontinuity is simply a result of compressed external fields and densities, then the external field strengths must be about 8 μG. As was shown in DCP, cluster fields of this magnitude are adequate to cause the observed large RMs across the source, both for the case of random fields with cell size ~ 20 kpc and for the case of organized loops. We now consider the two possibilities for the location of the Faraday screen in more detail.

If we assume the majority of the observed RM is caused by the sheath, we are led to one of two unpalatable scenarios. First, we could assume that the magnetic fields in the region of the bow shock originate in normal adiabatic shock compression of cluster fields of 7.5 μG and also assume that the geometry of the cluster fields is somehow such as to reduce the cluster contribution to the RM, e.g., cell sizes $\ll 20$ kpc. However, this runs into severe problems in the lobes back toward the core, where observed RMs are larger while the sheath density should be smaller (cf. Norman *et al.* 1982), as well as contradicting the observed large-scale ordering of the RM distribution. Second, we could assume a much weaker cluster field, with some other process creating relatively large magnetic fields in the sheath. However, this mechanism must operate over the short downstream distances implied by the observed RM distribution at the bow shock. As we noted in DCP, a natural candidate for such a process is a partial mixing along the contact discontinuity of the high density thermal gas of the sheath with the internal radio-emitting fluid, which has large magnetic fields. We do not believe this is occurring for three reasons: (1) in this case, one would expect very low fractional polarization along the source edges at 6 cm due to internal Faraday rotation, whereas the opposite is observed; (2) one would expect a systematic increase in RM toward the edges of the lobes, which is also not observed; and (3) we feel the RM discontinuity represents the location of the bow shock, not the contact discontinuity.

A much simpler model is to assume that the large-scale RM distribution, with amplitudes ≤ 4000 rad m^{-2}, is caused by the ambient cluster gas, with fields ~ 7.5 μG, while the smaller scale fluctuations (amplitudes ≤ 1000 rad m^{-2}) are a result of the shock-compressed external fields in the sheath. In addition to simplicity, the larger scale of the cluster gas (scales ≥ 10 kpc) compared to the thickness of the sheath seems more likely to be able to explain the large-scale ordering of the overall RM distribution (although we do not claim to understand this ord-

[4] Internal hot spot pressures are applicable, since we assume pressure balance between shocked IGM and jet material along the contact discontinuity.

ering of fields yet), while the RM contributions of the sheath might then account for the smaller scale (≤ 5 kpc) variations in some of the regions of high surface brightness (e.g., the bright ridge in the southwest lobe; see DCP).

The main problem with this last scenario is the magnitude of the required cluster magnetic fields, as has been discussed at length in DCP. We continue the argument here in the light of two recent observations of cluster magnetic fields by Kim *et al.* (1986), and Hennesy (1987). From detailed observations of the Coma cluster, Kim *et al.* derive cluster fields of 1 μG, and cell sizes of about 10 kpc. The work by Hennesy was a study of RMs for sources behind Abell clusters. He finds an upper limit to excess RMs from clusters of 55 rad m^{-2}, which implies mean line-of-sight fields through the cluster of ≤ 0.07 μG. He also finds a possible increase in depolarization of sources behind clusters, which would imply small cell sizes (≤ 10 kpc), and larger fields (~ 1 μG).

Our estimates for the field strength in the Cygnus cluster seem to be about an order of magnitude larger than is observed in most other clusters. This may be related to the fact that, unlike Coma and the majority of clusters in the Hennesy study, the Cygnus A cluster is a very dense cooling flow cluster, contains a large cD galaxy and contains a powerful radio source. In fact, the next closest example of a powerful double radio galaxy located at the center of a cooling flow cluster, 3C 295, also shows extraordinary RM structure, with magnitudes $\geq 10^4$ rad m^{-2} (R. Perley, private communication). Further, Baum (1987), has found a marked decrease in fractional polarization for sources preferentially associated with cD galaxies in dense clusters and suggests that large RMs caused by the dense local environment could be responsible (note: the effect was not isolated to classical doubles). However, the exact relationship between these factors (i.e., cD, cooling flow, and powerful radio source) and the large RMs remains unclear, as does the reason for the observed large-scale ordering of the cluster field.

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CHRIS CARILLI and RICK PERLEY: NRAO-VLA, P.O. Box 0, Soccoro, NM 87801

JOHN DREHER: 26-315, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139