EXTREME ROTATION MEASURE RADIO GALAXIES

Measuring Cluster Magnetic Fields

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1. Cygnus A: The First Case

Slysh (1966) first pointed out the bizarre properties of the polarized emission from Cygnus A: a strong wavelength dependence on fractional polarization, and a large difference in rotation measures (RMs) for the (integrated) emission from each lobe. These properties were confirmed, but not resolved, in the work of Mitton (1971) and Alexander et al.. (1984).

The resolution of the puzzle came with the multifrequency VLA observations of Cygnus A by Dreher et al.. (1987). They found that Cygnus A is located behind a deep 'Faraday screen' of magnetized, ionized plasma, producing large RMs (up to 5000 rad m^{-2} in magnitude), and gradients in RM (over 1000 rad m^{-2} $arcsec^{-1}$) across the lobes. The latest measurement of the Faraday screen towards Cygnus A is shown in Perley and Carilli (1996). The RM distribution across Cygnus A is not random, but shows ordered structure on scales up to 30 kpc. The RM structure is typically not correlated with total intensity structure. The tail of the southern lobe shows the largest RM values, and a generally 'noisier' RM distribution than for the rest of the source. This behavior for the southern lobe is consistent with the Laing-Garrington effect and the fact that the southern lobe is the un-jetted lobe in Cygnus A.

Before discussing the location of the RM screen in detail, we first mention two other interesting results from the polarization imaging of Cygnus A. One result is the magnetic field distribution (see Dreher et al.. 1987). The projected fields follow very closely the hard edges of the hot spots and radio lobes, and run parallel to the brighter lobes and filaments in the radio source. This morphology is consistent with simple kinematic dynamo effects for a 'frozen-in' magnetic field. The second result is the fractional

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polarization (FPOL) distribution (see Figs. 8 and 9 in Perley and Carilli 1996). FPOLs at 8 GHz range between 10% and 40% in most regions of the source. The one notable exception is the tail of the northern lobe, where FPOLs are 70% over a region almost 20 kpc in size. This is close to the theoretical maximum for an isotropic distribution (in pitch angle) of electrons in a uniform magnetic field, implying almost perfectly ordered fields (in projection) on scales of 20 kpc in the lobes of Cygnus A!

Dreher et al. consider, and reject in a trivial way, a Galactic origin for the large RMs seen towards Cygnus A. They also reject thermal material mixed with the radio lobes as the cause of the large RMs, on the mathematically rigorous basis that the wavelength dependence of observed position angle (PA) remains precisely quadratic for total rotations $>> 2\pi$ radians, without any depolarization with increasing wavelength. This argument has been strengthened with new observations at 8 GHz (Perley and Carilli 1996). They argue that the most likely location of the magnetized screen is the hot, X-ray emitting cluster gas in Cygnus A. The Cygnus A radio source is located at the center of a dense, massive 'cooling flow' cluster atmosphere, with $\approx 10^{14}$ $M_\odot$ of hot gas extending one Mpc from the cluster center (Carilli et al.. 1994). Using the cluster thermal gas density profile and the observed RM distribution, Dreher et al.. derive cluster magnetic field strengths between 5 and 10 μG, for cell sizes between 50 and 10 kpc.

Subsequent analysis of the RM screen towards Cygnus A has revealed that the shocked intracluster medium (ICM) enveloping the supersonically expanding radio source also contributes to the observed rotation measure distribution. The evidence came in the form of detection of an 'arc' of discontinuous change in rotation measure (RM) roughly concentric with the primary hotspot in the northern lobe, with a standoff distance of about $3''$ (see Carilli et al.. 1988). This jump in RM signals the point at which the thermal particles and tangential magnetic fields in the ICM are compressed by the shock due to the supersonic advance of the primary hotspot. Detecting this radio quiet bow shock both confirms the double shock structure expected at a jet terminus, and dictates the three dimensional geometry of the source. It also is relevant to the interpretation of the RM screen. The observed RM change at the bow shock implies pre-shock intracluster fields of 8 μG. Hence, Carilli et al.. propose a simple model in which the large-scale RM distribution towards Cygnus A (amplitudes up to 5000 rad m^{-2}, typical scale-sizes $\approx$ 10 to 30 kpc) is caused by the unperturbed cluster atmosphere, while small scale fluctuations (amplitude $\leq$ 1000 rad m^{-2}, scale-sizes $\leq$ 5 kpc) can result from the interaction of the source and the ambient medium.

An alternative model has been proposed by Bicknell et al. (1990), in which the RM screen is located in a thin mixing layer along the contact discontinuity (CD) between the shocked ICM and the radio lobe. In support of this model they point out that the 'striations' in the RM distribution perpendicular to the length of the lobes are suggestive of KH instabilities along the CD. Arguments against this model are the perfect quadratic dependence with wavelength of the observed PAs, and the lack of any 'depolarized skin' along the edge of the radio lobes.

2. Extreme RMs towards Cluster Center Radio Sources

Since the detection of extreme RMs towards Cygnus A, a number of studies have shown that such extreme RMs are characteristic of radio sources at the centers of dense X-ray emitting cluster atmospheres. A summary of these results can be found in Taylor, Barton, and Ge (1994). The most extreme case to date is that of 3C295, which shows RM values up to 20000 rad m^{-2}. A good correlation between cluster X-ray 'cooling flow' rate, and maximum observed RM values, has been demonstrated by Taylor et al... The sources in their study have various radio luminosities and morphological types, ranging from FRI (edge-darkened) sources such as Virgo A and Hydra A, to FRII (edge-brightened) sources such as Cygnus A. The single unifying element for these sources is that they all are located within 100 kpc of the X-ray cluster center. Standard models for radio source hydrodynamic evolution imply that the interaction between the ICM and the radio source is significantly different for FRI vs. FRII sources. This difference can be used to argue that extreme RMs are predominantly a large scale cluster phenomenon, rather than strictly a result of source-ICM interaction.

In parallel with imaging studies of RM screens towards cluster center radio sources, a number of studies have been made of RMs for background radio sources at various impact parameters towards known optical clusters (Kim et al. 1990, Hennessey et al. 1989). Theses studies are different than the imaging studies, in that: (i) the clusters are optically selected, (ii) the impact parameters involved are typically large (out to a few Mpc in some cases), and (3) the RM values are calculated from integrated radio source emission. Still, the results show a clear, and large, increase in the scatter of RM values for sources at impact parameters below a couple hundred kpc. The important implication is that extreme RMs are strictly a cluster center phenomenon. It can be shown (using typical X-ray cluster density profiles) that the bulk of the integrated RM through a cluster occurs in the first 100 kpc or so of pathlength from the cluster center.

In summary, the detection of extreme RMs towards Cygnus A, and subsequently in other cluster-center radio galaxies, shows that the thermal cluster atmospheres must be substantially magnetized, with fields $\geq$ a few μG. In most cases the pressure in the intracluster fields is below the thermal energy density (e.g. the plasma β-factor = ratio of thermal to magnetic pressure is about 30 for the Cygnus A cluster), implying a minor dynamical role for the fields. Even dynamically unimportant fields alter substantially the thermal conductivity of the plasma, and hence are very important when considering the cooling and heating of the ICM (Sarazin 1988). Models for the origin of intracluster fields include: the dynamo action of turbulent wakes of galaxies, injection of fields by previous outbursts of the radio source, ram pressure stripping of fields from galaxies, and amplification of a primordial field (see Sarazin 1988). Another possible mechanism for generating large scale cluster fields is amplification of seed fields during the merger of two clusters. Eilek (1995) presents a detailed 'Zeldovich rope dynamo' model for field generation in a cluster with net-helical turbulence, presumably driven by galaxy motions. She finds that the fields eventually evolve to equipartition strengths. She predicts RM distributions towards cluster center sources which compare well with observations, both in amplitude and structure.

The correlation between extreme RMs and cluster X-ray luminosity raises the possibility of searching for high redshift clusters by using radio polarization measurements. Detection of cluster atmospheres at redshifts ≥ 2 would present a severe challenge to current models for formation of such atmospheres, and for formation of large scale structure in general. We have begun a search for extreme RMs in a large sample of high redshift radio galaxies (Carilli et al.. 1996). In a sample of 40 radio galaxies at z > 2 we find a lower limit of 20% to the fraction of sources in the sample which show rest-frame RMs ≥ 1000 rad m^{-2}. The most extreme case thus far is 1138-262 at $z = 2.156$, which shows a maximum RM magnitude of 6250 rad m^{-2} (Röttgering et al. 1995, Athreya et al., this volume). The naive conclusion, based on results for lower redshift radio galaxies, would be that a substantial fraction of high redshift sources are situated at the centers of dense, X-ray emitting cluster atmospheres. This conclusion could be verified through deep X-ray imaging of a few extreme RM sources at high redshift.

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