Extreme Rotation Measure Radio Galaxies: Cluster Atmospheres at High Redshift

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Rich clusters of galaxies constitute the extreme high mass end of the cosmic mass distribution function, and study of such rare objects provides unique leverage into theories of structure formation in the universe (Peebles 1993). Unfortunately, optical studies of distant clusters can be corrupted by field galaxy contamination (Frenk et al. 1990), while searching for X-ray emission from cluster atmospheres at z $>$ 1 requires very long integration times for marginal detections. Thus far the three most distant X-ray cluster candidates currently known are all associated with powerful radio sources at z $\approx$ 1 (Crawford and Fabian 1993, Crawford and Fabian 1995, Dickinson 1997, Worrall et al. 1994).

One of the more important results in the study of extragalactic radio sources in the past 10 years has been the discovery of extreme values of Faraday rotation toward extended radio emitting structures (Dreher, Carilli, and Perley 1987, Taylor, Barton, and Ge 1994, Carilli et al. 1997a). Rotation measure (RM) values up to 20000 rad m^{-2} have been detected, as well as gradients in RM $\geq$ 1000 rad m^{-2} arcsec^{-1}. Observations of lower redshift radio galaxies have shown a clear correlation between extreme rotation measures and cluster environment: all sources located at the centers of dense, X-ray emitting cluster atmospheres show large amounts of Faraday rotation (Taylor et al. 1994). An important point is that this correlation is independent of radio source luminosity and morphological class, and hence is most likely a probe of cluster properties, and not radio source properties. The implication is that the hot cluster gas must be substantially magnetized, with field strengths of order a few μG.

The correlation between cluster X-ray properties and extreme rotation measures provides a potentially powerful criterion for selecting high z sources for deep X-ray observations. The best example to date is the narrow emission line radio galaxy PKS 1138$-$262 at z = 2.156. This source has the largest known RM at z $>$ 2, with (rest frame) RM values up to 6250 rad m^{-2} (Carilli et al. 1997b). The optical continuum morphology of 1138$-$262 is comprised of many blue 'knots' of emission, distributed over an area of about 100 kpc (Figure 1). The Lyα emission shows similar clumpy structure on a similar scale. Pentericci et al. (1997) interpret this distribution as a group of star forming galaxies in the act of merging into a giant elliptical galaxy. The radio source has the most disturbed morphology of any z $>$ 2 radio galaxy yet identified, indicating strong interaction between the radio jet and the ambient medium. Such interaction is supported by optical spectroscopy, showing large velocities, and velocity dispersions, for the line emitting gas in regions associated with the brightest radio knots. All these data provide strong, although circumstantial, evidence that the 1138$-$262 radio source is in a dense environment, perhaps a hot, cluster-type atmosphere.

Deep X-ray imaging with ROSAT of 1138$-$262 appears to confirm the existence of a dense cluster atmosphere enveloping the radio source. The ROSAT observation shows a clear detection of an X-ray source close to the position of the radio and optical nucleus of 1138$-$262 (Figure 2). The optical, radio, and X-ray data all favor a hot cluster gas origin for the X-rays from 1138$-$262, however

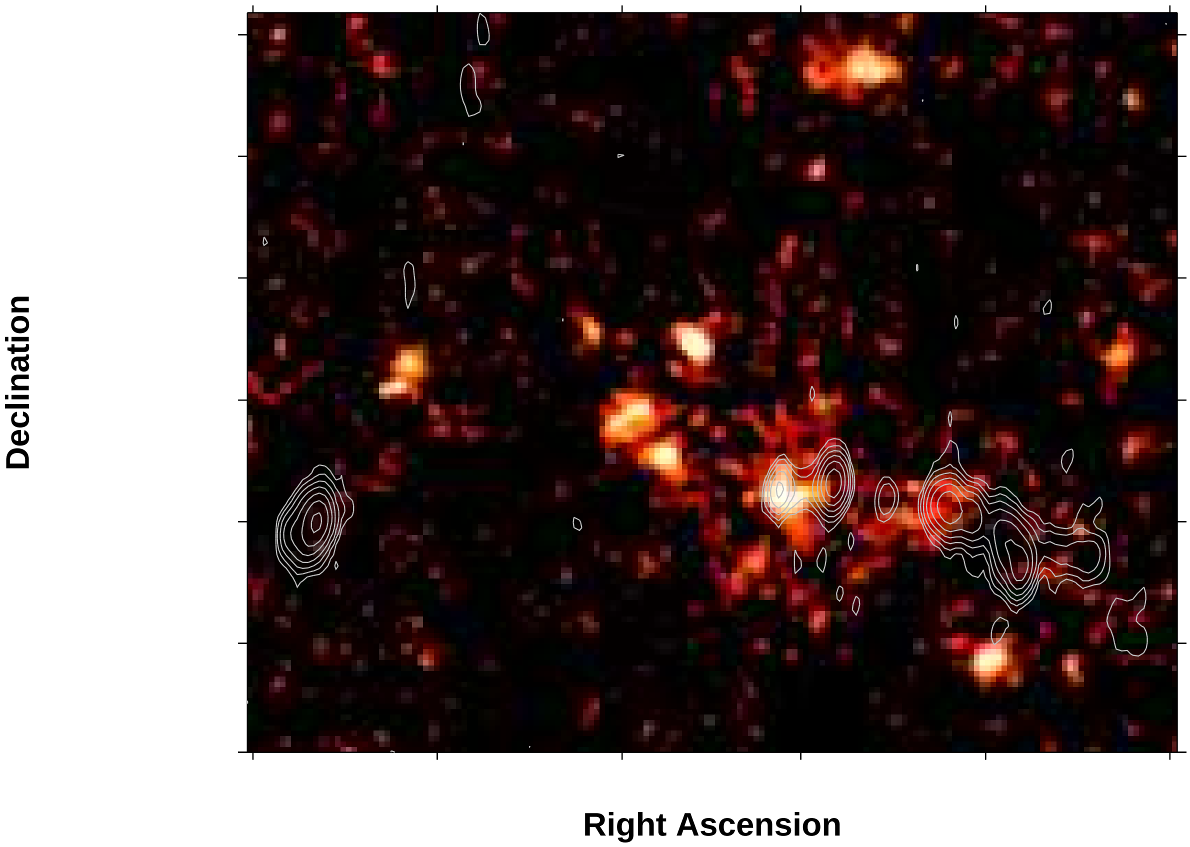

Figure 1. The VLA radio image of the z = 2.156 extreme rotation measure radio galaxy 1138−262 at 5 GHz (contours) with a resolution of 0.4″×0.7″. The grey-scale shows the HST image of 1138−262 (Pentericci et al. 1997, 1998). The fields size in RA is 13″.

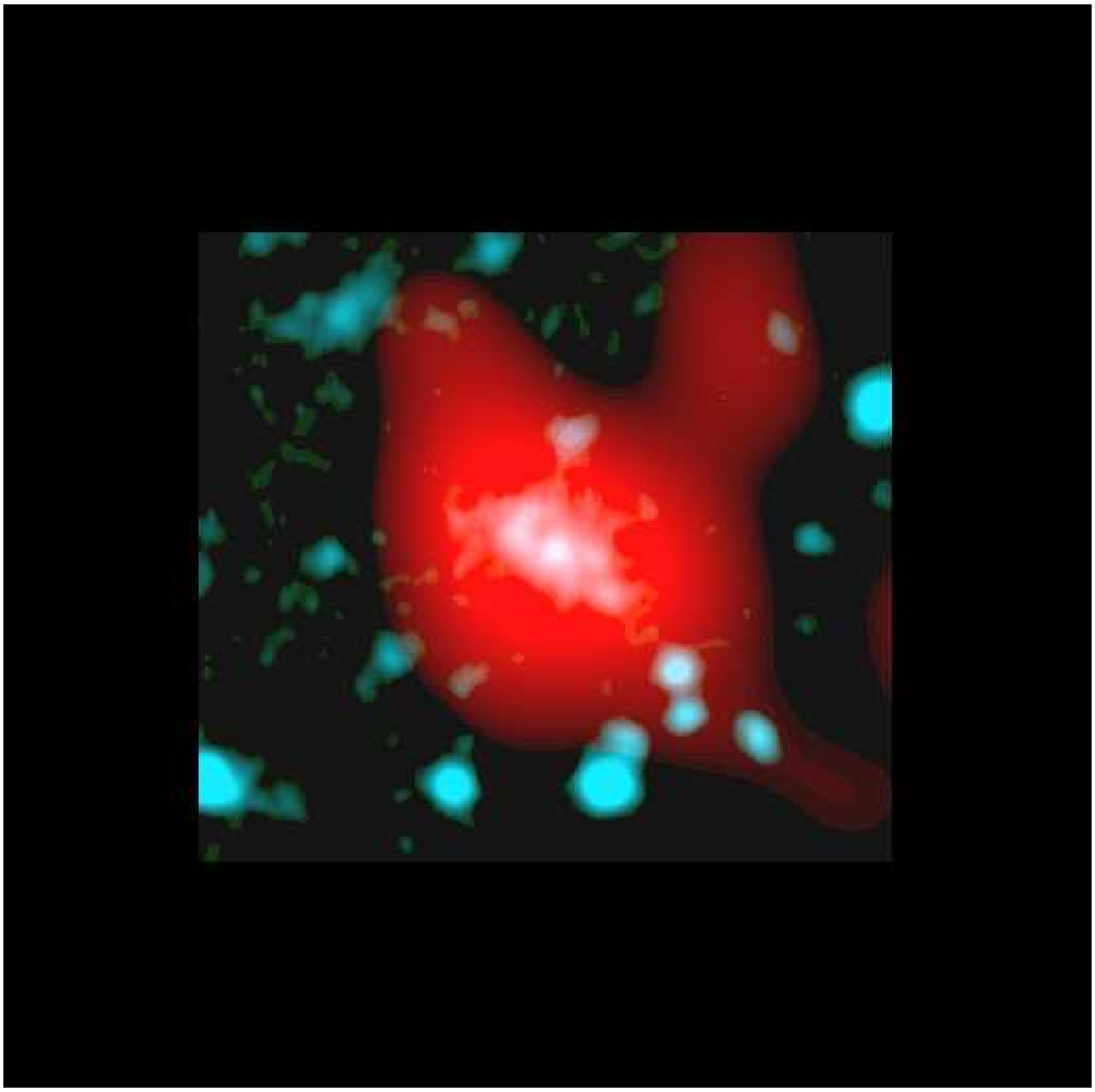

Figure 2. The X-ray image of 1138−262 from a 41 ksec exposure with the ROSAT HRI is shown in red (from Carilli et al. 1998). The image has been convolved with a Gaussian beam of FWHM = 10″, and a mean background level of 5 counts per beam has been subtracted. The X-ray luminosity for 1138−262 is $1.7 \pm 0.3 \times 10^{44}$ h^{-2} ergs sec^{-1} for emitted energies between 2 keV and 10 keV. The blue shows the optical image of 1138−262. The field size is 40″.

we cannot preclude an AGN contribution (see Carilli et al. 1998 for a detailed discussion). If the X-ray emission is from a hot cluster atmosphere, then the total gravitational mass is a few$\times 10^{14}$ $M_{\odot}$, and the total gas mass is a few$\times 10^{13}$ $M_{\odot}$.

The observations of the extreme RM radio galaxy 1138$-$262 have a number of interesting implications:

- Models for structure formation such as CDM using standard cosmologies predict that any large scale structure observed at $z \approx 2$ must be dynamically young, having just separated from the general expansion of the universe (Peebles 1993). Alternatively, massive structures at large redshift might indicate an open universe ($\Omega < 1$), or a finite cosmological constant.

- The existence of a hot cluster-type atmosphere at high redshift would argue for shock heated, primordial in-fall as the origin of the cluster gas, rather than ejecta from cluster galaxies (Sarazin 1986). Such a model would require an early epoch of star formation in order to supply the metals observed in the associated optical nebulosity (Ostriker and Gnedin 1996).

- The large rotation measures observed raise the question of the origin of cluster magnetic fields at early epochs. One possible mechanism is amplification of seed fields by a turbulent dynamo operating during the formation process of the cluster as driven by successive accretion events (Loeb and Mao 1994).

- The observation of X-ray emission from 1138$-$262 would then verify the technique of using extreme rotation measure sources as targets for searches for cluster X-ray emission at high redshift. Thus far there have been a total of 11 radio galaxies at $z > 2$ with source frame rotation measures greater than 1000 rad m^{-2}, the most distant being at $z = 3.8$ (Carilli et al. 1997b, Ramana et al. 1998, Carilli, Owen, and Harris 1994).

- An interesting alternative to a massive cluster atmosphere giving rise to the X-ray emission from 1138$-$262 is thermal emission from a 'maximal cooling flow', ie. a very dense, sub-cluster 'halo', perhaps associated with the (forming) cD galaxy on a scale $\leq$ 100 kpc (Fabian 1991).

The Case for the VLA Upgrade

An upgraded VLA could dramatically improve the capabilities to search for, and study, extreme RM radio sources at high redshift through the combination of increased sensitivity and resolution at lower frequencies (1.4 GHz and 2.3 GHz). High z radio galaxies are typically smaller than a few arcseconds, and they must be well resolved in order to properly determine the rotation measure distributions across the radio lobes. Current searches have been limited to the largest sources, and to frequencies of 5 GHz and higher. The steep spectrum nature of the extended radio emission in high z radio galaxies implies that such searches delineate, for the most part, the high surface brightness radio hot spots and core. The high radio frequency in the rest frame of the sources implies that only very large RM's can be detected ($\geq$ 1000 rad m^{-2}).

The upgraded VLA will have a sensitivity and resolution adequate to image the RM distribution across the radio lobes at a resolution of $0.1''$ at 1.4 GHz and 2.3 GHz. This capability should discover many new extreme RM radio galaxies at high redshift, and provide much more reliable rotation measure estimates, especially for RM's $\leq$ a few hundred rad m^{-2}. These sources can then be studied using modern X-ray and optical telescopes, to verify the existence of massive clusters at high redshift.

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