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Investigating the intergalactic medium in galaxy groups

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We present results from a new multifaceted study of bent-double lobed radio sources in galaxy groups. Bent-double sources, sometimes referred to as either wide or narrow angle tails, have long been associated with the high density, high velocity dispersion, and turbulent environment of massive clusters. Ram pressure resulting from either the motion of the source through a dense medium or the "cluster weather" is most likely responsible for bending these jets. We focus our attention on a sample of such sources in groups where the velocity dispersion is significantly lower. From new multi-frequency radio continuum observations using the GMRT and EVLA, we measure the jet properties, power and width as well as curvature. Combined with new optical spectroscopy obtained with SALT to measure the velocity dispersion of the environment in which these bent-double sources reside, we derive an estimate of the density of the intergalactic medium in these groups. The implication of our study is that groups may contain a significant amount of baryons that remain largely undetected in X-ray surveys of groups.

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1. Introduction

Galaxy groups are ubiquitous, intermediate density structures spanning the range between isolated field galaxies and rich clusters. According to the hierarchical scenario of the formation of large-scale structure, groups are the building blocks of rich clusters of galaxies (e.g. [13]). Thus, understanding the physical properties of clusters and their member galaxies requires knowledge of the extent to which galaxy evolution occurs in the group environment. The impact of the intergalactic medium on the evolution of individual galaxies is a critical factor in understanding how the environment affects galaxy evolution. The density of the intergalactic gas in groups has important implications for the effectiveness of ram pressure stripping, especially for low mass galaxies, and for the baryonic content of these systems. Groups are likely to contain a significant fraction of all the baryons in the local universe (e.g. [9, 14]).

One of the challenges in extragalactic astronomy continues to be accounting for the full baryonic content of the local Universe. A plethora of studies convincingly demonstrate that the predictions of the baryon budget from Big Bang nucleosynthesis (e.g. [9]) and the cosmic microwave background (CMB) are consistent with measurements of the baryonic content of the Universe at high redshift. At z=0, however, up to 60% of the baryons are "missing," unaccounted for in surveys spanning a wide range of observations techniques (e.g. [9, 10, 2, 11]). The baryon deficit scales with the depth of the potential well such that the deficit is minimized in the most massive clusters and most dramatic on the scale of individual galaxies (e.g. [11, 1, 5]).

Most censuses of the local baryons take into account stars, cold gas, and hot, X-ray emitting gas (e.g. [5, 12]) with the baryonic content of the most massive clusters being dominated by the hot gas. Cosmological simulations, however, predict that most of the baryons reside in a warm-hot intergalactic medium (WHIM) that pervades large-scale structure formation with low density and temperatures of $10^5 - 10^7$ K [3, 6].

As the temperatures of the WHIM are often too low for X-ray emission, the most common method employed to study the WHIM has been absorption lines arising from the O VI doublet ($\lambda\lambda$ 1032, 1038) associated with the Lyα forest [17]. The use of QSO absorption lines, however, is limited because the results are only tracing individual sight lines through the intervening medium.

We have taken a novel approach to measuring the density of the intergalactic medium (IGM) and baryonic content of galaxy groups through its effect on the jets of radio galaxies [7, 8]. As a double lobed radio source travels through the intergalactic gas, ram pressure causes its jets to be swept back. Although it had been thought that these sources require a dense IGM only found in rich clusters, a surprising number have been found in lower mass systems. Freeland et al. 2011 [8] derive IGM densities in the range of $10^{-4} - 10^{-3}$ cm^{-3} for a small sample of seven groups. They also place an upper limit of 2×10^6 K on the temperature of the IGM for two groups, a factor of 5–10 less than typical temperatures of hot gas observed in X-ray detected groups. The work discussed here seeks to expand on previous work [8] by expanding the sample size of bent-double sources and more thoroughly measuring the jet properties.

2. Methods

To understand how the shape of the radio tail can trace the density of the IGM, we start with the assumption that the radio tail is in pressure equilibrium with the intergalactic medium [15, 18]. We then find:

$$n_{\rm IGM} = 3\beta P_{\rm tail}\, \mu m_{\rm H} \sigma_v^2. \tag{2.1}$$

Here, $P_{\rm tail}$ is the pressure in the tail, β is the ratio of the mean kinetic energy of the group galaxies to the gas thermal energy, μ is the mean molecular weight, $n_{\rm IGM}$ is the density of the IGM, and σ is the velocity dispersion [18]. The pressure in the tail is derived from the observed radio intensity, spectral index, volume, and estimates of the ratio of relativistic proton to electron energy:

$$P_{\rm min} = (2\pi)^{\frac{-3}{7}} \left(\frac{7}{12}\right) \left[\frac{c_{12} L_{\rm rad}(1+k)}{\phi V}\right]^{\frac{4}{7}} \text{erg cm}^{-3}. \tag{2.2}$$

Here, c_{12} is a constant which depends on the spectral index, k is the ratio of the relativistic proton to relativistic electron energy and usually taken to be equal to 1, V is the volume, and ϕ is the filling factor. The bending of the jet implies that it is no longer in pressure equilibrium and that the intergalactic density must be quite high.

One can also use Euler's equation and a measure of the radius of curvature of the jet to estimate the ram pressure acting on the jet [18]. Euler's equation describes the balance of internal and external pressure gradients for a non-relativistic, hydrodynamic jet:

$$\frac{\rho_{\rm IGM} v_g^2}{h} = \frac{\rho_j v_j^2}{R}. \tag{2.3}$$

Here, $\rho_{IGM} v_g^2$ is the external ram pressure, $\rho_j v_j^2$ is the jet ram pressure, h is the radius of the jet, and R is the radius of curvature. High resolution radio continuum observations are used to measure $\rho_j v_j^2$, R, and h. We equate the velocity of the source as the difference between its velocity and the mean velocity of the surrounding galaxies which requires accurately measuring the velocity distributions of the environment.

3. Sample selection

We have compiled a sample of bent double lobed radio sources identified from the Faint Images of the Radio Sky at Twenty-centimeters (FIRST) survey [19]. Our targeted sources were selected such that they do not reside in known cluster. We preferred sources with higher surface brightness and symmetric jet curvature (estimated by eye). Where possible, we selected bent doubles with declinations$< +10^\circ$ to allow us to use SALT to measure the velocity dispersion of the host group. We assembled a sample of 30 bent doubles; FIRST cutouts of six of these sources are shown in Fig. 1.

4. Data

We use the Giant Metrewave Radio Telescope (GMRT) to obtain radio continuum images at 610 and 235 MHz which we can combine with FIRST survey 1.4 GHz images. We have also observed a subset of our sample with the Very Long Baseline Array (VLBA) at 5 and 1.6 GHz to directly measure the radius and spectral index of the jet. Additionally, we will determine where the

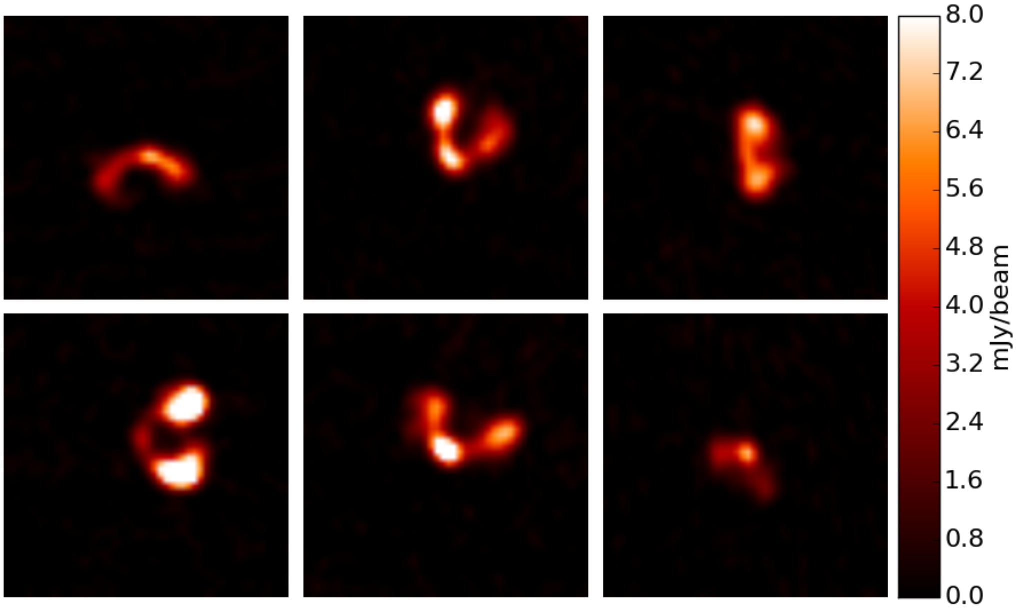

Figure 1: FIRST survey cutouts of five bent-double sources in our sample which we have observed with the GMRT and VLBA. Each image is a 1.5' square. The redshift range of these sources is 0.12–0.22.

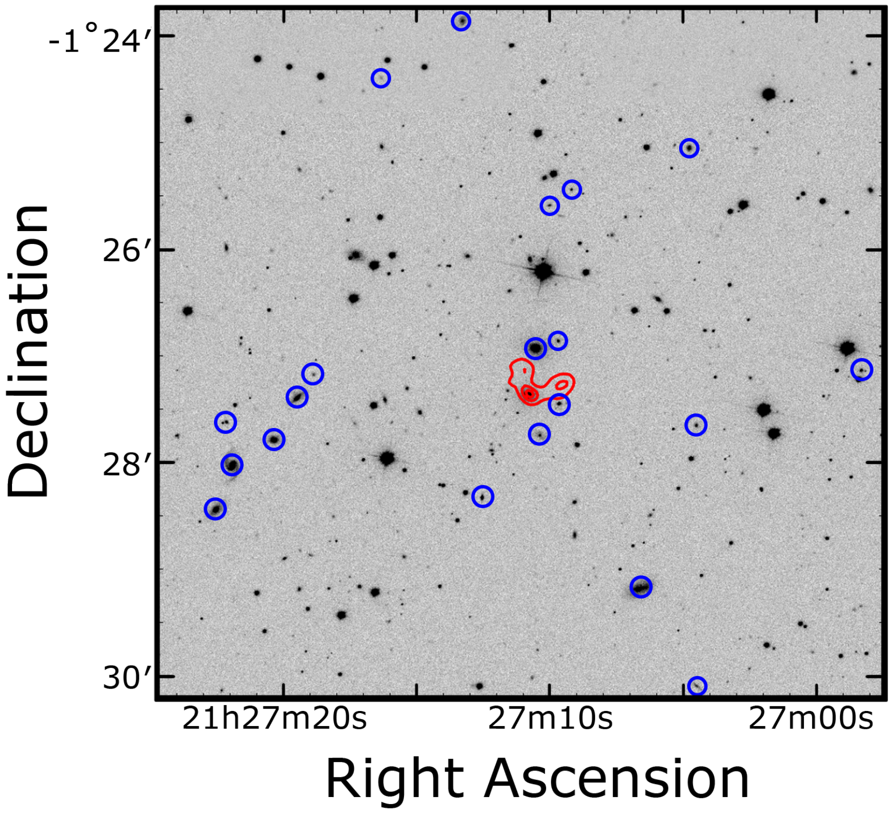

Figure 2: 1.4 GHz FIRST radio contours of a bent double source from our sample overlaid on a SDSS optical image. Blue circles indicate galaxies observed with SALT MOS.

bending of the jet begins with respect to the host galaxy. An optical image of a group in our sample with a radio contour overlay is shown in Fig. 2.

To build velocity distributions for our sample, we carry out Mulit-object Spectroscopy (MOS) measurements with the South African Large Telescope (SALT). For each group, we observe one or two slitmask configurations of 15–20 slits on target galaxies. Galaxies observed with one slitmask for a sample group are shown in Fig. 2.

We are in the process of reducing and extracting the spectra to derive redshifts for galaxies. Example spectra from one field are shown in Fig. 3.

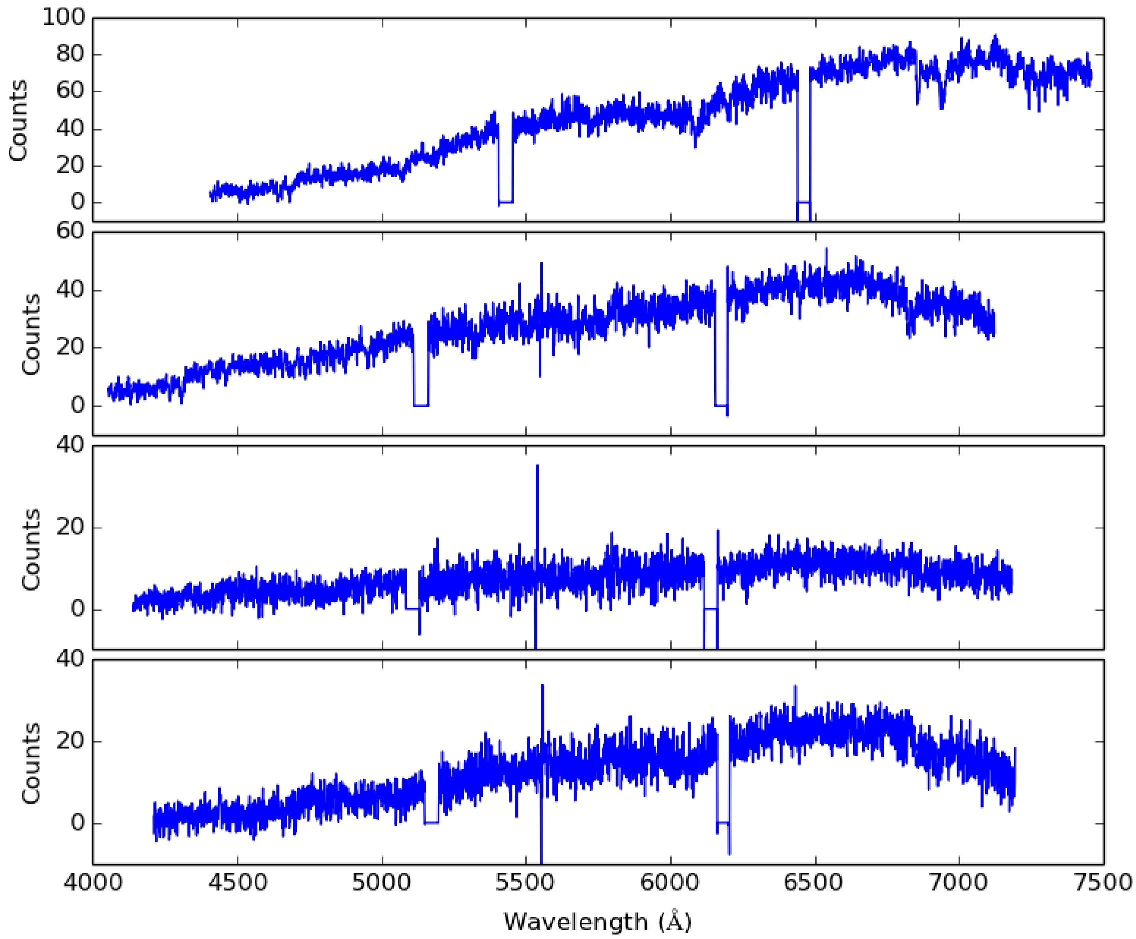

Figure 3: Example spectra from the field shown in Fig. 2.

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References

[1] Andreon, S. 2010, *The stellar mass fraction and baryon content of galaxy clusters and groups*, *MNRAS*, 407, 263, [arXiv:1004.2785]

[2] Bregman, J. N. 2007, *The Search for the Missing Baryons at Low Redshift*, *ARA&A*, 45, 221, [arXiv:0706.1787]

[3] Cen, R. & J. P. Ostriker 1999, *Where Are the Baryons?*, *ApJ*, 514, 1, [arXiv:astro-ph/9806281]

[4] Croston, J. H., M. J. Hardcastle, & M. Birkinshaw 2005, *Evidence for radio-source heating of groups*, *MNRAS*, 357, 279, [arXiv:astro-ph/0411413]

[5] Dai, X., et al. 2010, *On the Baryon Fractions in Clusters and Groups of Galaxies*, *ApJ*, 719, 119, [arXiv:0911.2230]

[6] Davé, R., et al. 2001, *Baryons in the Warm-Hot Intergalactic Medium*, *ApJ*, 552, 473, [arXiv:astro-ph/0007217]

[7] Freeland, E., R. F. Cardoso, & E. Wilcots 2008, *Bent-Double Radio Sources as Probes of Intergalactic Gas*, *ApJ*, 685, 858, [arXiv:0806.3971]

[8] Freeland, E. & E. Wilcots 2011, *Intergalactic Gas in Groups of Galaxies: Implications for Dwarf Spheroidal Formation and the Missing Baryons Problem*, *ApJ*, 738, 145, [arXiv:1107.0965]

[9] Fukugita, M., C. J. Hogan, & P. J. E. Peebles 1998, *The Cosmic Baryon Budget*, *ApJ*, 503, 518, [arXiv:astro-ph/9712020]

[10] Fukugita, M. & P. J. E. Peebles 2004, *The Cosmic Energy Inventory*, *ApJ*, 616, 643, [arXiv:astro-ph/0406095]

[11] Giodini, S., et al. 2009, *Stellar and Total Baryon Mass Fractions in Groups and Clusters Since Redshift 1*, *ApJ*, 703, 982, [arXiv:0904.0448]

[12] Laganá, T. F., et al. 2013, *A comprehensive picture of baryons in groups and clusters of galaxies*, *A&A*, 555, A66, [arXiv:1304.6061]

[13] McGee, S. L., et al. 2009, *The accretion of galaxies into groups and clusters*, *MNRAS*, 400, 937, [arXiv:0908.0750]

[14] Mulchaey, J. S. 2000, *X-ray Properties of Groups of Galaxies*, *ARA&A*, 38, 289, [arXiv:astro-ph/0009379]

[15] Stocke, J. T. & J. O. Burns 1987, *B2 0800+24 - A narrow-angle tail radio galaxy in a small group of galaxies*, *ApJ*, 319, 671

[16] Sun, M., et al. 2009, *Chandra Studies of the X-Ray Gas Properties of Galaxy Groups*, *ApJ*, 693, 1142, [arXiv:0805.2320]

[17] Tripp, T. M., B. D. Savage, & E. B. Jenkins 2000, *Intervening O VI Quasar Absorption Systems at Low Redshift: A Significant Baryon Reservoir*, *ApJ*, 534, L1, [arXiv:astro-ph/0003277]

[18] Venkatesan, T. C. A., et al. 1994, *Why do head-tail sources exist in poor clusters of galaxies?*, *ApJ*, 436, 67

[19] Wing, J. D. & E. L. Blanton 2011, *Galaxy Cluster Environments of Radio Sources*, *AJ*, 141, 88, [arXiv:1008.1099]