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# RADIO MODE FEEDBACK VIA BCGS IN COOL CORE CLUSTERS

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**Abstract.** Brightest Cluster Galaxies (BCGs) are the most extreme and interesting population of luminous and massive galaxies known within the cluster environment. Nearly all BCGs tend to show radio emission with radio jets varying in size from a few kpc to Mpc scale with various morphological and spectral details (FRI, FRII, WAT, NAT, twisted jets, relic emission etc.). At optical wavelengths many BCGs show ionised emission line (H-alpha) nebula with a range of different morphological structures (extended filaments, one directional plumes, centrally concentrated, extended but quiescent, etc.) but often have an inner disc region with rotational velocities ranging from 100 to several hundred km/s whose axis of rotation is aligned with the radio jets. We perform a combined optical (VIMOS, MUSE) /radio (GMRT, VLA) study of BCGs and derive a correlation between the disc and jet properties (alignment, radio power, rotational velocity, dominance of the disc etc.). We then discuss these correlations in the context of feedback and mergers in the cluster environment. This study is intended to understand the duty cycle (birth, evolution and death) of AGNs in cool core clusters and highlight the importance of low frequency observations in this field with sensitive instruments like LOFAR and SKA precursors (MeerKAT and ASKAP), that are now beginning to operate.

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## 1 Introduction

The central regions of massive galaxy clusters show intense X-ray emission suggesting that significant radiative cooling is occurring within the Intra Cluster Medium (ICM) (Fabian et al. 1981). This suggests that the gas should quickly lose energy, cool down and condense into cold gas clouds and/or form stars on timescales much shorter than the age of the cluster (Fabian 1994). However, the observed star formation rates (McNamara & O'Connell 1989) and cold gas masses (Braine & Dupraz 1994; McNamara & Jaffe 1994; O'Dea et al. 1994; Edge 2001; Salomé & Combes 2003) are insufficient to be consistent with the rate of gas cooling estimated from the X-ray data. Studies of highly sensitive X-ray spectral observations (Peterson et al. 2001; Tamura et al. 2001; Peterson et al. 2003) failed to detect the spectral signatures of gas cooling at ∼1 keV. Most importantly the FeXVII line, emitted by gas at 0.5–1 × $10^6$ K, is weak or absent in many cooling flow clusters. This suggests that some process is truncating the cooling of gas below $\sim frac1,3$ $T_{cluster}$ (one third of the clusters X-ray temperature), preventing the production of cooler gas (see review by Peterson & Fabian 2006).

The fact that the ICM core is rapidly radiating away most of its energy but shows significantly reduced cooling below a critical threshold ($\sim 10v$K) suggests that there must be some process injecting energy back into the cooling gas. Radio mode "feedback" from AGN is the only process consistent enough and energetic enough to provide the energy required to offset the energy loss in the most rapidly cooling cluster cores. This mechanical feedback, occurring as the radio jets (up to Mpc-scale) inflate massive cavities in the ICM (McNamara et al. 2005; McNamara & Nulsen 2007) is central to the growing consensus within the community. This hypothesis is further confirmed by the fact that almost all the BCGs tend to host radio jets. In the case of gas rich cool-core clusters, repeated radio outburst activity gives rise to rare relic emission (with $\alpha < -1.5$) usually in

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the peripheral regions of the jet that emits predominantly at lower frequencies Lane et al. (2004). However, the most rapidly cooling cluster cores ubiquitously contain optical line emitting nebula (at $\sim 10^4$ K) surrounding the BCG (Heckman et al. 1989; Cavagnolo et al. 2008). This suggests that despite the feedback some residual cooling must be present to produce this cool gas. Indeed this residual production of cool gas can provide the fuel required to drive the AGN outbursts from the BCG providing a potential mechanism to fine tune the radio feedback and maintain the X-ray properties observed.

## 2 The VOICES data

The Vimos Optical Ifu Cluster Emission line Survey (VOICES) was conduced by Hamer et al. (2016) to study the properties of the optical emission line nebula surrounding BCGs in rapidly cooling clusters. VOICES obtained and studied VIMOS IFU observations of 73 cluster cores known to contain optical line emitting nebula allowing these nebula to be studied in a statistically significant way for the first time. The study found that the line emitting nebula could be catagorised into five distinct morphological classes. The most common were quiescent objects, accounting for 62% of the sample, which were elliptical in structure, centrally concentrated and had a H$\alpha$ peak coincident with the continuum peak. Compact objects, making up just 4% of the sample, were similar but only extended on scales comparable to the seeing making their resolved properties difficult to constrain. Disturbed objects, which had made up the bulk of previously studied objects, accounted for just 17% of the sample. These objects had central H$\alpha$ peaks coincident with the continuum peak but show extended line emission with no ordered structure. The other two classifications show extended emission in just one preferential direction. The most common of these were plumes (12% of the sample) which has a H$\alpha$ peak close to the continuum peak and a lower surface brightness "tail" extending away from the BCG. The final classification were offset objects (just 5% of the sample) in which the majority of the H$\alpha$ emission is associated with a peak offset from the continuum peak by greater than twice the seeing.

The resolved kinematics of the sample suggested that the ionised nebula form a kpc scale disc like structure in the cores of many clusters. Kinimetry analysis (Krajnović et al. 2006; Shapiro et al. 2008) shows that 65% of the sample have kinematics which are consistent with discs. These are found in almost all of the quiescent systems but also within some of the compact objects and within the central regions of some disturbed objects. This suggests that such discs are common in cluster cores and may be an important component of the feedback process.

## 3 Optical Nebula and jet properties comparison

Multi wavelength studies of BCGs can give important insights into the role of the BCG in fueling the feedback process through radio outbursts. A combined optical and radio analysis allows us to investigate the impact of the kpc scale discs on the formation and activation of the radio outflows. Massive discs contain sufficient fuel to launch large scale and sustained radio jets while systems without discs (or with disturbed discs) lack a simple mechanism of funneling this fuel into the AGN accretion region. In Hamer et al. (2016) we identified five distinct morphologies of optical nebulae which may represent distinct evolutionary phases of the cluster core. We discuss below the comparison of radio data from 1.4 GHz down to 150 MHz with the optical data (1) for one example object from each of these morphological classifications:

**Hydra–A** is a BCG with a FR–I type radio morphology situated at the centre of a quiescent nebular of ionised gas. It shows the presence of a 5kpc disc of cold molecular and atomic gas whose axis of rotation is aligned with the radio jets (Hamer et al. 2014a). At 1.4 GHz the radio jets extend for ~100 kpc and show an S-shaped morphology. Deep MUSE observations of the system detect the presence of H$\alpha$ emission along the eastern edge of the high frequency radio emission. This suggests that the radio jets are directly interacting with the cool gas in this system however, the line emission is asymmetric about the jets following only the eastern edge. These observations are not sensitive enough to directly constrain the form of this interaction (entrainment, enhanced cooling from the compressed ICM etc.) nor if lower surface brightness emission is present on the western edge of the jets. At 150 MHz the emission is significantly more extended with lobes extending over 530 kpc retaining the orientation of the higher frequency jets. Lane et al. (2004) studied the low frequency emission of the jets down to 74 MHz with the VLSS data and suggested a presence of relic emission from the jet with a spectral index between 330 to 74 MHz for the core region, $\alpha = -0.48 \pm 0.03$, for the northern lobe region, $\alpha = -1.20 \pm 0.04$ and $\alpha = -1.5 \pm 0.1$ for the southern lobe. Our new GMRT data at 150 MHz confirms the presence of the diffuse relic emission from the lobes and allows us to measure the spectral index

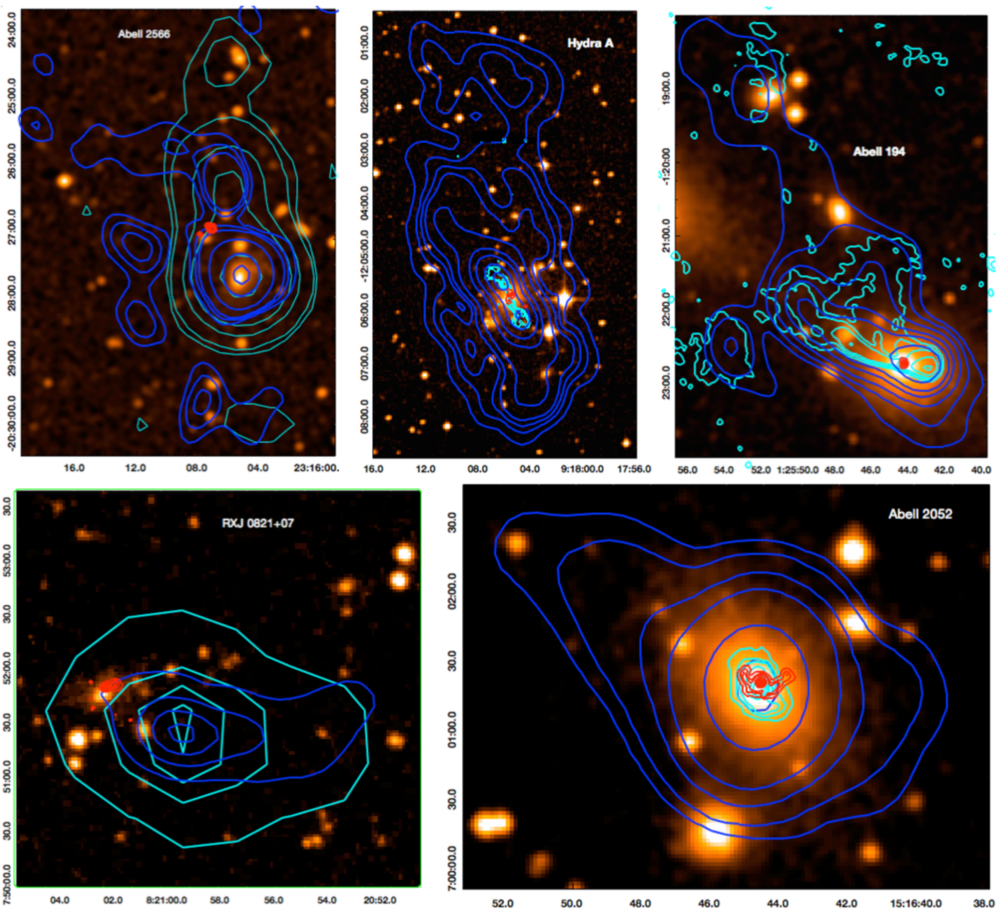

**Fig. 1.** DSS data on cool-core galaxy cluster with overlaid contours from VIMOS H-alpha disc emission (red), TGSS-GMRT 150 MHz (blue) and VLA 1.4 GHz (cyan). From left to right and top to bottom panels- Abell 2566 (offset H$\alpha$), Hydra A (quiescent H$\alpha$), Abell 194 (compact H$\alpha$), RXJ 0821+07 (plumed H$\alpha$) and Abell 2052 (disturbed H$\alpha$). Note that the red contours for the disc emission in Hydra A is measured with the MUSE/VLT.

for the complete structure between 1.4 GHz to 150 MHz at $\alpha = -0.86$. Lane et al. (2004) measure the life time of the lobes to be 47 Myr which is consistent with the age of the outburst estimated from black hole accretion rates and efficiencies (Wise et al. 2007).

**Abell 194** host a BCG with a very compact optical nebula that shows evidence of rotation. The BCG is associated with a narrow angle tailed (NAT) FR–I radio galaxy with jets extending up to 135 kpc at 1.5 GHz. GMRT data at 150 MHz shows a similar extent up to 142 kpc and more clearly traces diffuse emission in the northern jet (Sakelliou et al. 2008). The lobes have a spectral index of $\alpha = -0.51$ between 1.5 GHz and 150 MHz and an estimated age of 1.2 Gyr. The presence of a narrow angled tail in this system suggests that ram pressure is exerted on the radio jets as the galaxy moves through the ICM. This coupled with the central but small ionised nebula implies that this system may be in the late stages of a merger as cold gas begins to re-accumulate in the core.

**Abell 2052** hosts a disturbed optical nebular which shows no ordered velocity structure. The BCG is producing a FR-I type radio galaxy with radio emission at 1.4 GHz that fills the ICM cavities in the North/South direction. The optical nebula shows limbs of emission which extend around the edges of the northern radio lobe. The presence of gas here and the fact that the limbs show no ordered velocity structure suggest that they are likely related to the formation of the X-ray cavity, most likely gas entrained by the radio jet and pulled out of the central nebula. At 150 MHz the structure is much more extended, out to 120 kpc, and shows a sloshing jet morphology which causes spiral structures that can also be seen in the X-ray emission. The spectral index between 1.4 GHz and 150 MHz varies significantly between $\alpha = -0.5$ in the core region and $\alpha = -2.5$ near the edges, suggesting a presence of relic emission surrounding the BCG. However, deep low frequency radio observations are needed to confirm the morphology, size and excess emission at 150 MHz of the jet structure.

**The BCG in RXJ 0821+07** contains a plumed optical nebula with evidence of a disc in the central bright region. The radio source is a head-tail galaxy with an extension of 346 kpc that is barely resolved at 1.2 GHz. At 150 MHz the head-tail structure is clearly resolved and extends from the BCG over a similar extent to the higher frequency data. More diffuse emission at 1.4 GHz is detected as compared to 150 MHz, with a clear offset between the peak of the radio and the optical emission. Further deep radio observations are needed in this BCG, at low radio frequencies in order to confirm the radio counterpart, its morphology and extent of the diffuse emission. The spectral index is -0.9 above 1.4 GHz and gets steeper, $\alpha < -1.2$ at lower frequencies suggesting that there are overlapping regions of plasma with different ages.

**Abell 2566** has a bright centrally peaked nebula that is completely offset from the BCG that shows no evidence of rotation. The BCG hosts an FR-I radio source which is extended in the north/south direction over ~600 kpc. The presence of line emission offset from the BCG is typically associated with gas sloshing within the core of the BCG (Hamer et al. 2014b) which is possibly being caused by an interaction. The GMRT data shows a bend in the 150 MHz radio morphology to the north of the extent which also suggests sloshing, hence consistent with the optical data. This structure extends over 660 kpc and has a spectral index between 1.4 GHz and 150 MHz of $\alpha = -1.22 \pm 0.02$.

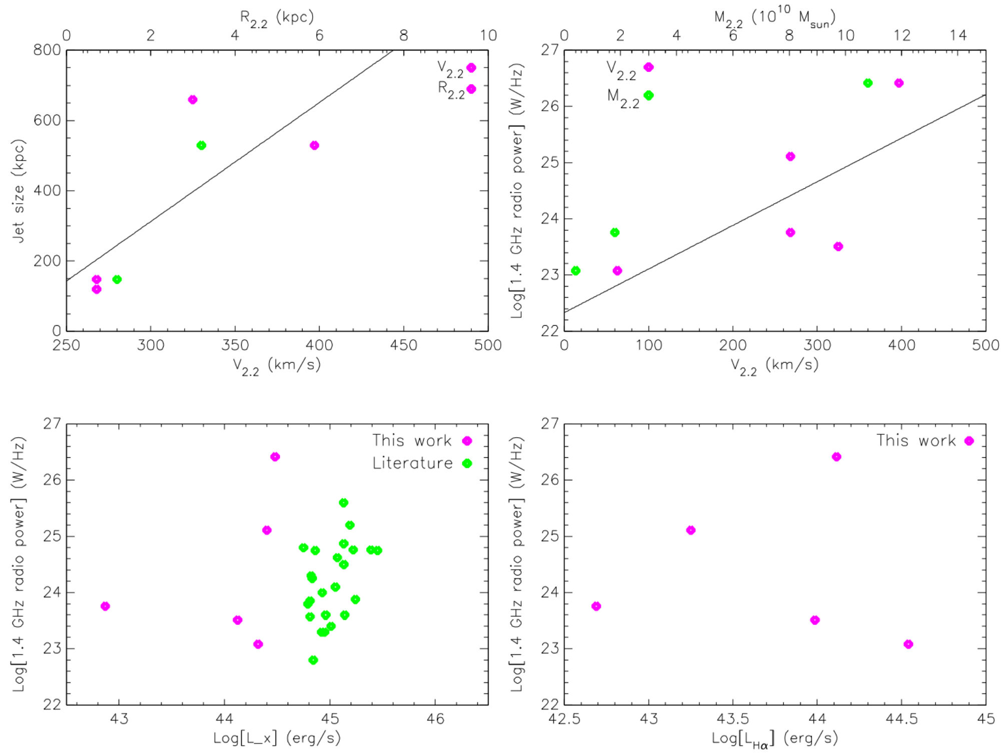

**Fig. 2.** A comparison of the radio properties with the optical and X-ray properties of the cluster. *Top left*: Extent of the jet plotted against the peak rotational amplitude and flattening radius of the disc. *Top right*: 1.4 GHz radio power against the peak rotational amplitude and the dynamical mass of the disc. *Bottom left*: 1.4 GHz radio power against the X-ray luminosity. *Bottom right*: 1.4 GHz radio power against the Hα luminosity. Purple points are those derived from this study, green points are taken from the literature.

In figure 2 we compare the properties of the radio jets with those of the optical nebulae and the cluster X-ray emission. We find that the jet size is well correlated with the disc properties (rotational velocity, disc size and dynamical mass) and the radio power increases as the rotational velocity increases. This suggests that more stable discs are launching larger jets while smaller and disturbed discs launch smaller jets. There is some trend of radio power with $L_{H\alpha}$ suggesting the outliers may have a different evolution. This might be expected as more larger more massive discs imply higher orbital angular momentum which will produce a more powerful jet through the BlandfordZnajek process (Blandford & Znajek 1977).

## 4 Conclusions

Radio sources from BCGs have a large variation in size (100–700kpc) with various morphologies (FRI, FRII, WAT, NAT, head-tail etc.). The largest most powerful jets are produced in the most massive and stable discs suggesting discs are an important part of the feedback process. The presence of aged plasma in the ICM suggests that the outbursts are periodic and repeated suggesting feedback is not always on in all systems. We suggest a feedback duty cycle based on the morphological classifications discussed above. Compact objects, which host radio loud AGN are systems which are just beginning to accrete gas and drive outbutrsts. As gas accumulates the disc grows forming a quiescent object driving large radio lobes and retaining some relic emission. Finally the feedback outpaces the accretion disturbing the disc, less fuel is available to drive the outbursts and the system is dominated by relic radio emission. The structure of the H$\alpha$ and radio in the offset and plumed objects are more consistent with mergers and may represent a separate evolution. Further low frequency observations in this field with sensitive instruments like LOFAR and SKA precursors (MeerKAT and ASKAP) will allow us to expand this analysis to more objects improving the statistics of this analysis.

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## References

Blandford, R. D. & Znajek, R. L. 1977, MNRAS, 179, 433
Braine, J. & Dupraz, C. 1994, A&A, 283, 407
Cavagnolo, K. W., Donahue, M., Voit, G. M., & Sun, M. 2008, ApJ, 683, L107
Edge, A. C. 2001, MNRAS, 328, 762
Fabian, A. C. 1994, ARA&A, 32, 277
Fabian, A. C., Hu, E. M., Cowie, L. L., & Grindlay, J. 1981, ApJ, 248, 47
Hamer, S. L., Edge, A. C., Swinbank, A. M., et al. 2014a, MNRAS, 437, 862
Hamer, S. L., Edge, A. C., Swinbank, A. M., et al. 2014b, MNRAS, 437, 862
Hamer, S. L., Edge, A. C., Swinbank, A. M., et al. 2016, MNRAS, 460, 1758
Heckman, T. M., Baum, S. A., van Breugel, W. J. M., & McCarthy, P. 1989, ApJ, 338, 48
Krajnović, D., Cappellari, M., de Zeeuw, P. T., & Copin, Y. 2006, MNRAS, 366, 787
Lane, W. M., Clarke, T. E., Taylor, G. B., Perley, R. A., & Kassim, N. E. 2004, AJ, 127, 48
McNamara, B. R. & Jaffe, W. 1994, A&A, 281, 673
McNamara, B. R. & Nulsen, P. E. J. 2007, ARA&A, 45, 117
McNamara, B. R., Nulsen, P. E. J., Wise, M. W., et al. 2005, Nature, 433, 45
McNamara, B. R. & O'Connell, R. W. 1989, AJ, 98, 2018
O'Dea, C. P., Baum, S. A., Maloney, P. R., Tacconi, L. J., & Sparks, W. B. 1994, ApJ, 422, 467
Peterson, J. R. & Fabian, A. C. 2006, Phys. Rep., 427, 1
Peterson, J. R., Kahn, S. M., Paerels, F. B. S., et al. 2003, ApJ, 590, 207
Peterson, J. R., Paerels, F. B. S., Kaastra, J. S., et al. 2001, A&A, 365, L104
Sakelliou, I., Hardcastle, M. J., & Jetha, N. N. 2008, MNRAS, 384, 87
Salomé, P. & Combes, F. 2003, A&A, 412, 657
Shapiro, K. L., Genzel, R., Förster Schreiber, N. M., et al. 2008, ApJ, 682, 231
Tamura, T., Kaastra, J. S., Peterson, J. R., et al. 2001, A&A, 365, L87
Wise, M. W., McNamara, B. R., Nulsen, P. E. J., Houck, J. C., & David, L. P. 2007, ApJ, 659, 1153