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=) The conclusions are a bit long-winded. Could cut some.

A RELATIONSHIP BETWEEN AGN JET POWER AND RADIO LUMINOSITY

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ABSTRACT

Using X-ray data collected with the *Chandra* X-ray Observatory and multi-frequency VLA radio data, we investigate the scaling relationship between active galactic nucleus jet power, $P_{\rm jet}$, and observed radio luminosity, $L_{\rm radio}$. We seek to determine if the $P_{\rm jet}$-$L_{\rm radio}$ scaling relations presented in Bîrzan et al. (2008) for primarily brightest cluster galaxies (BCGs) are continuous in form and scatter from isolated giant elliptical galaxies (gEs) up to BCGs. We expand the sample used in Bîrzan et al. (2008) to lower radio power by incorporating measurements for 21 relatively isolated gEs. Combining our results with those presented in Bîrzan et al. (2008), we find a mean scaling relation of $P_{\rm jet} \approx 4 \times 10^{16}\ L_{\rm radio}^{0.68}$ erg s^{-1} with a scatter of ≈ 0.7 dex. We briefly comment on the consistency of our results with theoretical models, specifically those of Blandford & Konigl (1979) and Willott et al. (1999). Our results are consistent with models for confined radio sources that are close to minimum energy density with jet hadron to lepton energy ratios of $\gtrsim 100$. We also discuss the importance of environment when measuring a $P_{\rm jet}$-$L_{\rm radio}$ relation, and a possible connection to the process of entrainment. A brief discussion of the implications and utility of our results for large-scale structure formation models is also included.

Ck

Subject headings: galaxies: active – galaxies: clusters: general – X-rays: galaxies – radio continuum: galaxies

1. INTRODUCTION

Observational evidence accumulated over the last decade indicates that most galaxies harbor a central supermassive black hole (SMBH) which has co-evolved with the host galaxy, giving rise to the well-known correlations between bulge luminosity, stellar velocity dispersion, and central black hole mass (Kormendy & Richstone 1995; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Marconi & Hunt 2003; Best et al. 2005). The prevailing explanation for these tight correlations is that they result from galaxy mergers and the influence of feedback from active galactic nuclei (AGN) on galaxy evolution (*e.g.* Silk & Rees 1998; Kauffmann & Haehnelt 2000). Around the same time, the *Chandra* X-ray Observatory (Weisskopf et al. 2000) direct evidence for ~~advanced the importance of~~ AGN feedback when observations unambiguously revealed AGN induced cavities and shock fronts in the X-ray emitting gas surrounding many massive galaxies (*e.g.* McNamara et al. 2000; Fabian et al. 2000; Schindler et al. 2001). - others?

Run-on sentence

Wrong Reference

It was recognized that X-ray cavities provide an accurate gauge of the total mechanical energy and mean jet power produced by SMBHs (McNamara et al. 2000). Jet powers, $P_{\rm jet}$, are approximated using estimates of cavity age and measure~~ment of the pV work done by an~~ AGN in excavating a cavity (see McNamara & Nulsen 2007, for a reviews). Several detailed studies of cavities have shown that AGN feedback supplies enough energy to regulate star formation and suppress cooling of the hot halos of galaxies and clusters (Bîrzan et al. 2004; Dunn et al. 2005; Rafferty et al. 2006; Dunn & Fabian 2008; Bîrzan et al. 2008). Likewise, the existence of correlations between low core entropy, short central cooling time, cooling luminosity, and $P_{\rm jet}$ indicate the presence of a finely-tuned ~~environmental heating and cooling~~ feedback loop (Cavagnolo et al. 2008; Rafferty et al. 2008; Cavagnolo et al. 2009). - Mittal et al 09, Voit & Donahue 08

Anderson & Fabian 06

- Diehl et al. 08

The mounting observational evidence has changed our view of galaxy formation, and a consensus has emerged that AGN feedback plays an important role in suppressing star formation in bulges at late times. includes ~~Invoking~~ energetic feedback from AGN in numerical simulations has been shown to bring the shape and normalization of the galaxy luminosity function into better agreement with observations (Croton et al. 2006; Bower et al. 2006; Saro et al. 2006; Sijacki et al. 2007). However, the details of how AGN ~~feedback is~~ coupled ~~to~~ the ~~thermodynamics of an~~ environment are still ~~being debated~~ poorly understood (De Young et al. 2008; Mathur et al. 2009). ~~One~~ long-standing problem barrier to a better theoretical and observational understanding of heating via AGN is reliably estimating total AGN kinetic output ~~for large statistical samples~~ (*e.g.* Rawlings & Saunders 1991; Ledlow & Owen 1996).

lots more refs.

To this end, the study of X-ray cavities have yielded constraints on the fundamental properties of AGN jets. But, the systematic study of large samples using the X-ray cavity technique is limited by factors such as cavity size, cavity projection on the sky, contrast between ambient medium & cavity surface brightness, and observational ~~parameters~~ issues such as exposure time and angular resolution (Bîrzan et al. 2009). Therefore, measuring and calibrating correlations between simple observables, like ~~AGN~~ radio power ($L_{\rm radio}$), and AGN energetics (*e.g.* $P_{\rm jet}$) is vital to ~~circumvent the need for deep X-ray observing programs.~~ A robust $P_{\rm jet}$-$L_{\rm radio}$ scaling relation could then be applied to measurements from current and future all-sky radio surveys (*e.g.* NVSS, SUMSS, LOFAR, SKA) to study SMBH formation history and subsequent AGN mechanical heating of the Universe (Croton et al. 2006; Sijacki & Springel 2006).

An observational $P_{\rm jet}$-$L_{\rm radio}$ relationship for a sample of primarily BCGs was presented in Bîrzan et al. (2004, hereafter

A bit awkward - be direct.

A reliable relationship between jet power and radio power ~~would~~ enable feedback studies across universe.

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Come up with better term than "isolated" - How about "lower mass/luminosity"?

B04) and Bîrzan et al. (2008, hereafter B08). In B08, scaling relations between $P_{\rm jet}$ and 327 MHz, 1.4 GHz, and bolometric radio luminosities were presented. B08 showed that $P_{\rm jet} \propto L_{\rm radio}^{0.5-0.7}$ depending on the choice of frequency. However, there are few objects in the B08 study with $L_{\rm radio} \lesssim 10^{38}$erg s^{-1} and $P_{\rm cav} \lesssim 10^{43}$erg s^{-1}, *i.e.* the region populated by low-power radio galaxies ~~like~~ isolated gEs. in

In this paper we re-visit the B08 $P_{\rm jet}$-$L_{\rm radio}$ study with the inclusion of 21 gEs. Combining the B08 results and the results in this paper, we find a relationship between jet power and radio power which is similar at high and low radio frequencies. The relationships span 6-8 orders of magnitude in $P_{\rm jet}$ and $L_{\rm radio}$, and have the general form $P_{\rm jet} \sim 10^{43}(L_{\rm radio}/10^{40})^{0.7}$erg s^{-1} with dominantly intrinsic scatter of ~ 0.7 dex. We also find encouraging similarity between our best-fit relations, previous studies, and theoretical AGN models.

include in abstract?

This paper is structured as follows: §2 outlines the sample of selected gEs. X-ray and radio data reduction is discussed in §3. Results and discussion are presented in §4. The summary and concluding remarks are given in §5. A ΛCDM cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 0.27$, and $\Omega_\Lambda = 0.73$ is adopted throughout. All quoted uncertainties are 68% confidence. Hereafter, the terminology cavity power and jet power are used interchangeably, and are denoted as $P_{\rm cav}$ and $P_{\rm jet}$, respectively.

2. SAMPLE

Our sample of 21 gEs is taken from the sample of 160 gEs compiled by Jones et al. (in preparation). The B08 sample is taken from Rafferty et al. (2006, hereafter R06). Information regarding our gE sample is listed in Table 1. The Jones et al. compilation is drawn from the samples of Beuing et al. (1999) and O'Sullivan et al. (2003) using the criteria that $L_K > 10^{10}$ $L_\odot$ and the object has been observed with *Chandra*. Of the 160 gEs, extended X-ray emission was detected in 109 objects. AGN activity was suspected in 27 objects based solely on the presence of surface brightness depressions in the X-ray emitting gas. We have further excluded dwarf galaxies ($M_V < -19.5$) from the sample since it is not clear that the substructure in the X-ray gas is associated with an AGN, leaving 21 objects. The 21 gEs in our sample are in relatively low density environments, *i.e.* these are not the central dominant or brightest galaxies in clusters or groups. The gEs studied here have X-ray halos and radio sources with luminosities lower than are typically found for cDs and BCGs.

K-band luminosity

redundant? covered by K-band cut?

3. OBSERVATIONS AND DATA ANALYSIS

3.1. *X-ray*

Outburst powers are determined in the usual manner from the X-ray data (see B04 and R06). Gas ~~properties~~ used here are taken from the analysis by Jones et al. (in preparation). Cavity locations and sizes are from Nulsen ~~et al.~~ (in preparation), with cavity volumes and their errors calculated by the method of B04, which takes into account the unknown cavity geometry. The enthalpy of each cavity is determined as $H_{\rm cav} = [\gamma/(\gamma-1)]pV$, where p is the gas pressure at the radius of the projected center of the cavity, and V is its volume, assuming $\gamma = 4/3$ for the ratio of specific heat capacities. To estimate the average power of an outburst, the enthalpy of each cavity is divided by an estimate of its age, ~~and~~ these values are summed for all the cavities in each system to obtain an estimate of the average outburst power of its AGN. For compatibility with B08, here we give results only for the buoyant energy

vague delete?

within the cavities.

age estimates, $t_{\rm buoy}$ (B04). Because the uncertainties are large (chiefly due to the volume estimates), errors are propagated in log space, assuming that the errors in the main inputs are independent. uncertain what means these?

3.2. *Radio*

Bolometric radio luminosities were estimated using the relation $\nu L_\nu = 4\pi D_L^2(1+z)^{\alpha-1}S_\nu\nu_0$, where S_ν is integrated flux density at frequency ν_0, z is redshift, D_L is luminosity distance, ν_0 is central beam frequency ~~of the measurements~~, and α is radio spectral index. We have assumed the radio spectra behave as $S_\nu \propto \nu^{-\alpha}$ with a spectral index of $\alpha = 0.8$, typical for ~~optically-thin, non-thermal~~ extragalactic radio galaxies (Condon 1992). The radio luminosities estimated using 200-400 MHz and 1.4 GHz fluxes are denoted as $L_{200-400}$ and $L_{1.4}$, respectively.

The 1.4 GHz continuum radio flux for each source was taken from the flux-limited NRAO VLA Sky Survey (NVSS, Condon et al. 1998). For NGC 1553, which is lies outside the NVSS survey area, the 843 MHz continuum radio flux was taken from the ~~flux-limited~~ Sydney University Molonglo Sky Survey (SUMSS, Bock et al. 1999; Mauch et al. 2003). The 1.4 GHz flux for N1553 was estimated using $\alpha = 0.89$, which was calculated from the 843 MHz SUMSS flux and 5 GHz Parkes flux (Whiteoak 1970).

The radio morphologies for our sample are heterogeneous: some sources are large and extended, while ~~some sources~~ others are compact. To ensure the entire radio source was measured, a fixed physical aperture of 1 Mpc was searched around the X-ray centroid of each target. For each target field, all detected radio sources were overlaid on a composite image of X-ray, optical (DSS I/II[7]), and infrared emission (2MASS[8]). When available, the deeper and higher resolution radio data from VLA FIRST[9] was included. A visual inspection was then performed to establish which ~~detected~~ radio sources were associated with the target gE. After confirming which radio sources within the search region were associated with the target gE, the fluxes of the individual sources were added and the associated uncertainties summed in quadrature.

Archival VLA data for each source in the sample was also reduced and analyzed. In the cases where high-resolution VLA archival data is available, multifrequency images were used to confirm the connection between NVSS detected radio sources and the host gE. Images at 1.4 GHz were further used to check NVSS fluxes. We found flux agreement for most sources, ~~with~~ the exceptions being IC 4296 and NGC 4782, where the NVSS flux is approximately a factor of 2 lower. These sources are unique because the radio lobes contain significant power in diffuse, extended emission which is not detected in NVSS. For these sources, the fluxes measured from the archival VLA data are used in our analysis. The additional data analysis step was also used to investigate the poorly confined sources discussed in Section §4. For the systems where nuclear radio emission was resolved, we found, on average $S_{\nu,\rm nucleus}/S_{\nu,\rm total} \lesssim 0.1$, suggesting the nuclear contribution to the low-resolution NVSS measurements has a negligible impact on our results. good

B08 found that using lower frequency radio data, *i.e.* 327 MHz versus 1400 MHz, resulted in a lower scatter $P_{\rm cav}$-$L_{\rm radio}$ relation. For our sample of gEs, the quality and availability of

[7] http://archive.stsci.edu/dss/
[8] http://www.ipac.caltech.edu/2mass/
[9] http://sundog.stsci.edu

"not ideal"

327 MHz data were poor, and thus we gathered low-frequency radio fluxes from the CATS Database[10] (Verkhodanov et al. 1997). CATS was queried in the frequency range 200-400 MHz using ~~the list of~~ radio source coordinates found from the NVSS and SUMSS searches. Of the 21 gEs in our sample, 17 objects were found in the CATS database with fluxes in the 200-400 MHz range. The approach used for searching CATS means that low-frequency radio emission without a 1.4 GHz counterpart will be missed. But, because CATS does not provide images for visual inspection, the search method also ensures that spurious detections are less likely to be included. Therefore, the 200-400 MHz radio powers shown in Figure 1 might underestimate the 200-400 MHz fluxes for these gEs. However, because of the large range of radio powers, a systematic shift by a factor of a few along the L_{radio} axis for all the gE points would ~~alters~~ the best-fit slope ~~within the uncertainties~~ negligibly.

unclear

4. RESULTS AND DISCUSSION

4.1. P_{jet}-L_{radio} Scaling Relation

The results from the X-ray and radio data analysis are shown in the plots of P_{cav}-$L_{1.4}$ and P_{cav}-$L_{200-400}$ presented in Figure 1. A subjective figure of merit (FOM) was assigned to each set of cavities – shown as color coding in Figure 1 and listed in Table 1. We assigned figures of merit because, currently, no standard algorithm for detecting cavities and determining their volumes exists. Thus the FOMs represent our qualitative visual assessment. FOM-A cavities are associated with AGN radio activity and have well-defined boundaries; FOM-B cavities are associated with AGN radio activity, but lack well-defined boundaries; FOM-C cavities have poorly-defined boundaries, and their connection to AGN radio activity is unclear. FOM-C cavities are excluded from all fitting.

Figure 1 shows a continuous power law relationship between cavity power and radio power over approximately 8 orders of magnitude in radio power and 6 orders of magnitude in cavity power. To determine the form of the power-law relation, we performed linear fits in log-space for each frequency regime using the bivariate correlated error and intrinsic scatter (BCES) algorithm (Akritas & Bershady 1996). The orthogonal BCES algorithm takes in asymmetric uncertainties for both variables, assumes the presence of intrinsic scatter, and performs a linear least-squares regression which minimizes the squared orthogonal distance to the best-fit relation. This differs from the fitting approach in B08 which minimized the distance in the P_{cav} coordinate. The best-fit parameter uncertainties were calculated using 10,000 Monte Carlo bootstrap resampling trials.

good

The best-fit orthogonal BCES determined linear function in log-space for the P_{cav}-$L_{1.4}$ and P_{cav}-$L_{200-400}$ relations are:

$$\log P_{cav} = 0.72\,(\pm 0.13)\,\log L_{1.4} + 1.92\,(\pm 0.17) \quad (1)$$

$$\log P_{cav} = 0.64\,(\pm 0.08)\,\log L_{200-400} + 1.55\,(\pm 0.12) \quad (2)$$

where P_{cav} has units 10^{42}erg s^{-1}, and $L_{1.4}$ and $L_{200-400}$ have units 10^{40}erg s^{-1}. The scatter for each relation is $\sigma_{1.4} = 0.77$ dex and $\sigma_{200-400} = 0.61$ dex, and the respective correlation coefficients are $r_{1.4} = 0.73$ and $r_{200-400} = 0.81$. We have quantified the total scatter about the best-fit relation using a weighted estimate of the orthogonal distances to the best-fit line (see Pratt et al. 2009~~, for equations~~). For comparison, the B08 scaling relations are

$$\log P_{cav} = 0.35\,(\pm 0.07)\,\log L_{1.4} + 1.85\,(\pm 0.10) \quad (3)$$

$$\log P_{cav} = 0.51\,(\pm 0.07)\,\log L_{327} + 1.51\,(\pm 0.12) \quad (4)$$

[10] http://www.sao.ru/cats/

where P_{cav} has units 10^{42}erg s^{-1}, and $L_{1.4}$ and L_{327} have units 10^{24} W Hz^{-1} (or $\approx 10^{40}$erg s^{-1}). The relations have scatters of $\sigma_{1.4} = 0.85$ dex and $\sigma_{327} = 0.81$ dex. ~~There is~~ an error in Equation 15 of B08 that has been corrected in Equation 4 (Bîrzan et al. 2009). Now

Note that ~~we find~~ a steeper relationship IN at 1.4 GHz than B08, ~~and~~ the slopes of the relations from this work agree to within the uncertainties. This difference in slope at 1.4 GHz between our work and B08 is due to the additional data points at lower P_{jet}. The B08 points tend to be clumped in a fairly narrow power range, which gave the few points at the upper and lower power extremes excessive leverage over the slope. The new data extends to lower jet powers, giving a more uniform sampling and a more robust measurement of the slope and zero point. good

As a simple check, we point out two systems with accurate estimates of AGN jet power: Cygnus A and Hercules A. For Cygnus A (point with largest L_{radio} in Figure 1), where our P_{jet}-L_{radio} relations appear to overestimate the jet power by ≈ 40, times the total kinetic luminosity of $\sim 2 \times 10^{46}$erg s^{-1} calculated by Wilson et al. (2006) using the shock is consistent with the P_{jet} value of $\sim 5 \times 10^{46}$erg s^{-1} predicted by our relations. Hercules A (which is not in the B08 sample) is a similar case to Cygnus A. With $P_{cav} = 310 \times 10^{42}$erg s^{-1} and $L_{1.4} = 4100 \times 10^{40}$erg s^{-1}, ~~placing~~ Hercules A falls in the same region of Figure 1 as Cygnus A. But, the total kinetic luminosity of $\sim 1.6 \times 10^{46}$erg s^{-1} calculated by Nulsen et al. (2005) using the shock agrees with the prediction from our relations, $\sim 3.2 \times 10^{46}$erg s^{-1}.

The substantial scatter in the P_{jet}-L_{radio} relations highlight that radio luminosity is an inaccurate surrogate for determining AGN power in individual systems. As seen in systems like Hydra A (Wise et al. 2007) or MS 0735.6+7421 (McNamara et al. 2005), the energetics can be dominated by the effects of an AGN outburst which is more powerful than average. This may be particularly true for gEs, which have lower pressure halos and are more susceptible to disruption by AGN outbursts (Weinmann et al. 2006; Puchwein et al. 2008). ~~However,~~ B08 showed that correcting for the effect of radio aging by including a scaling with break frequency does reduce the scatter within the relations ~~by~~ but by only $\approx 50\%$.

4.2. Comparison with Models and Observational Studies

Owing to the importance of prescriptions for kinetic feedback in galaxy formation models, ~~specifically in the form of a late-time radio-mode extension of the quasar era~~, establishing observational constraints ~~for the prescriptions is vital~~ are necessary (e.g. Heinz et al. 2007). There is a multitude of jet models (i.e. Longair et al. 1973; Scheuer 1974; Blandford & Rees 1974; Begelman & Cioffi 1989; Carvalho & O'Dea 2002a,b), ~~and~~ but we restrict our focus to models which specifically discuss the P_{jet}-L_{radio} relation. We also examine ~~previous~~ earlier observational studies of P_{jet}-L_{radio}~~, besides B08~~. In this section we use the common parameterization for jet power $L_{kin} = \eta L_{radio}^{\alpha}$, where L_{kin} is total kinetic jet power, η is some normalization, α is a scaling index, and L_{radio} is emergent synchrotron power.

For flat-spectrum compact radio cores (e.g. small scale jets and not radio lobes), the jet model by Blandford & Konigl (1979) predicts $\alpha = 12/17$ (≈ 0.71). Starting with the Blandford & Konigl (1979) model, Falcke & Biermann (1995) found a similar slope when assuming emergent jet power scales with accretion power in a jet-disk system. The more general~~ized~~ model for scale-invariant jets by Heinz & Sunyaev (2003) also predicts $\alpha = 12/17$. Utilizing a collection of objects from the R06 sample and 5 GHz core luminosities corrected for relativistic Doppler boosting, Merloni & Heinz (2007) found that $\alpha = 0.81$ with $\eta \approx 2 \times 10^{44}$erg s^{-1} with $L_{\rm radio}$ in units of 10^{40}erg s^{-1}. The earlier study by Heinz & Grimm (2005) using 5 GHz core luminosities and an estimate of $L_{\rm kin}$ from the Galactic X-ray binary mass-radio-X-ray fundamental plane relation (Gallo et al. 2003; Merloni et al. 2003) found, when $L_{\rm kin} \propto L_{\rm radio}^{12/17}$ was held constant, $\eta \approx 6 \times 10^{44}$erg s^{-1} with $L_{\rm radio}$ in units of 10^{40}erg s^{-1}

This is muddled make clear

Willott et al. (1999, hereafter W99) derive α and η using the hypersonic jet model of Falle (1991), and assuming radio lobes are at minimum energy density (see Miley 1980, for details). W99 derived $\alpha = 6/7$ with $\eta \approx f^{3/2}\ 4.61 \times 10^{41}$erg s^{-1} when $L_{\rm radio}$ is in units of 10^{40}erg s^{-1}. The normalization has been adjusted from 151 MHz to 1.4 GHz assuming $\alpha = 0.8$. The factor f consolidates a variety of unknowns (see W99 for details). The fiducial W99 model ($f = 1$) yields η two orders of magnitude lower than our best-fit normalizations. Because the W99 model has been widely used for estimating jet power, the difference in η's needs to be explored.

lot of 6/7 is close to our value

The W99 normalization has a weak dependence on ambient gas density. Using shallower and lower density gas profiles consistent with observations increases jet outflow velocities in the W99 model, which in turn increases η by factors of $\sim 2-5$. In addition, there is a critical dependence on the fractional deviation from the minimum-energy condition and k, which is the ratio of energy in neutralizing species to electrons. We find that for k lying in the range of tens to hundreds, values consistent with observational findings (Dunn et al. 2005, 2006; De Young 2006; Bîrzan et al. 2008), brings the W99 normalization into agreement with our work. Figure 2 shows that the W99 zero-point lies significantly below our best-fit $P_{\rm jet}$-$L_{\rm radio}$ relations, but the slopes formally agree. W99 find that to fit their model to narrow-line region luminosities (assuming $L_{\rm NLR} \propto L_{\rm kin}$) for sources in the 7C and 3CRR surveys, f must equal 20, which is the upper-limit of f in their model and implies $k \approx 20$.

sentence is unclear

✓

many

4.3. *Poorly Confined Sources*

In Figure 2 is a set of points highlighting systems we have classified as being poorly confined (PC). The objects are: IC 4296 (Killeen & Bicknell 1988; Pellegrini et al. 2003), NGC 315 (Bridle et al. 1979; Willis et al. 1981), NGC 4261 (Jones & Wehrle 1997; Jones et al. 2000), NGC 4782 (Machacek et al. 2007), and NGC 7626 (Birkinshaw & Davies 1985). These objects were culled from the sample because the X-ray surface brightness decrements are reminiscent of tunnels rather than bubbles, and the radio morphologies are distinctly different from the rest of the gE and B08 objects. X-ray cavities typically enclose the jet+lobe radio emission, see Figure 3 for an example in M84. However, for the PC sources, the only indication of gas excavation in the X-ray halo is found near the base of the jets, seemingly at the "edge" of the X-ray halo, see Figure 3 for an example in NGC 4261. The appearance of breaking-out from the X-ray halo is our reason for suggesting these sources are poorly confined.

The observed ~~small voids~~ tunnels do not capture the total $p\,dV$ work being done by the jets. ~~However,~~ There Here may be cavities which are not imaged extending to larger radii and enclosing the radio lobes. But, for PC systems the ambient medium at those radii is too faint to yield a cavity detection. To test this, We calculated $P_{\rm cav}$ values for the PC systems assuming radio lobe morphology approximates the volume of cavities potentially at larger radii. Pressure profiles were extrapolated to large radii using the best-fit parameters of a β-model (Cavaliere & Fusco-Femiano 1978) fit to the surface brightness profile, assuming the ambient atmosphere is isothermal, and adding a background gas pressure of 10^{-13} dyne cm^{-2}. The assumed background gas pressure is based on the mean value observed in the outskirts of clusters and groups. See the *ACCEPT* database[11] for a catalog of such pressure profiles. Cavity ages were calculated assuming expansion at the gas sound speed. As a result of the radio lobes extending into regions where the pressure profiles are very steep and approaching the background pressure, the large volumes are offset by much lower pressures and longer ages, resulting in modest values of $P_{\rm cav}$. Because we do not have a robust measurement of $P_{\rm cav}$ for the PC systems, they were excluded from the preceding analysis of the $P_{\rm jet}$-$L_{\rm radio}$ relations.

Ref. the case

Two of the PC sources, NGC 315 and NGC 4261, are part of a sample of nine FR-I objects analyzed in detail by Croston et al. (2008a, hereafter C08) using *XMM-Newton* X-ray observations. Provided in C08 are the $4pV$ enthalpies for each FR-I source (calculated using the radio lobe volumes and the external thermal pressure at the lobe mid-point), and the mean temperature of the group environments into which the lobes are expanding. Assuming lobe expansion occurs at the ambient gas sound speed, we calculated $P_{\rm cav}$ values for each of the C08 FR-I sources. For N315 and N4261 we find no significant difference between the $P_{\rm cav}$ values calculated using the *Chandra* data and the *XMM-Newton* data from C08. Using the NVSS search method outlined in Section 3.2 we calculated $L_{1.4}$ for each C08 FR-I source. Our PC objects and the C08 FR-I objects are plotted in Figure 2.

do you mean this?

Figure 2 shows that the PC and C08 FR-I sources reside well below our best-fit relation. This discrepancy implies that these sources have the lowest jet power per unit radio luminosity of all objects in the sample. One explanation is that these sources have lower k values, possibly because there are intrinsic differences in radio sources (light and heavy jets), or because all jets are born light and become heavy on large scales due to entrainment. Another explanation is that that PC sources are more powerful than our measurements indicate due to energy being ~~imparted to~~ shocks. On average, shock energy is a small correction to $P_{\rm cav}$, factor of a few in clusters (McNamara & Nulsen 2007), but the frequency and variety of AGN driven shocks is broad, ranging from strong (Mach $\gtrsim 2$) – Centaurus A (Kraft et al. 2003; Croston et al. 2009), NGC 3801 (Croston et al. 2007) – to weak (Mach $\lesssim 2$) – 3C 31 (Laing & Bridle 2002), Cygnus A (Wilson et al. 2006), Hydra A (Wise et al. 2007), Hercules A (Nulsen et al. 2005), M87 (Forman et al. 2007), MS 0735.6+7421 (McNamara et al. 2005), NGC 4552 (Machacek et al. 2006), NGC 4636 (Baldi et al. 2009), NGC 4782 (Machacek et al. 2007) – to definitively absent – 3C 186 (Siemiginowska et al. 2008), 3C 388 (Kraft et al. 2006), NGC 6764 (Croston et al. 2008b). However, this would require that the fraction of jet power going into shocks is preferentially higher for systems with relatively high implied radiative efficiencies (*i.e.* $P_{\rm jet}/L_{\rm radio} < \eta$).

change wording

This should be cut down. Too much to read.

5. SUMMARY AND CONCLUSIONS

We have presented analysis of the jet power-radio power versus scaling relation for a sample of 21 giant elliptical galaxies observed with the *Chandra* X-ray Observatory. Cavity pow-

[11] http://www.pa.msu.edu/astro/MC2/accept

ers, $P_{\rm jet}$, were calculated for each set of cavities using similar methods to those outlined in R06. Bolometric radio luminosities, $L_{\rm radio}$, were estimated using 1.4 GHz and 200-400 MHz fluxes taken from the NVSS/SUMSS surveys and the CATS database.

Incorporating the data from B08, we find a continuous power-law relation between $P_{\rm jet}$-$L_{\rm radio}$ covering 6 decades in $L_{\rm radio}$ and 8 decades in $P_{\rm jet}$ (Figure 1). ~~Using log-space orthogonal BCES fits,~~ We we find similar forms for the power laws describing the $P_{\rm jet}$-$L_{\rm radio}$ trend with the mean form $P_{\rm jet} \approx 5.93 \times 10^{43}(L_{\rm radio}/10^{40})^{0.68}$erg s^{-1}. This relation ~~comes with the caveat~~ of ≈ 0.7 dex scatter about the best-fit relations, ~~and we point out that the relation is weakly applicable for determining *total* AGN energy output of an individual system~~. We also note the general agreement of our best-fit relations with previous observational studies and predictions from theoretical jet models.

Several groups have applied the Bîrzan scaling relations to study the effects of AGN feedback on structure formation, (e.g. ~~most notably~~ Best et al. (2007) and Magliocchetti & Brüggen (2007), with some groups now suggesting that distributed low-power radio galaxies may dominate heating of the intracluster medium, *e.g.* Hart et al. (2009). Up to now, the available observational results, which were primarily calibrated to high-power radio sources, did not clearly indicate if a $P_{\rm jet}$-$L_{\rm radio}$ relation would be continuous, or of comparable scatter, for lower power radio sources. Assuming there is no redshift evolution of $P_{\rm jet}$-$L_{\rm radio}$, our relations suggest higher mass galaxies dominate over lower mass galaxies in the process of mechanical heating within clusters. The next step is to study the process of mechanical heating in a cosmological context, *e.g.* evaluating the contribution of mechanically dominated AGN on the bolometric AGN luminosity function over cosmic time Cattaneo & Best (2009).

We have also focused on a subset of objects we classify as being poorly confined (PC) by their environments (Figure 2). These objects have $P_{\rm jet}/L_{\rm radio}$ ratios which are large relative to the rest of our sample. In addition, PC sources reside in the same region of the $P_{\rm jet}$-$L_{\rm radio}$ plane as the FR-I sources taken from C08. ~~Possible explanations for the nature of these sources lie in the long-standing effort to understand the connection between properties of~~ radio galaxies and their ~~environment. Processes such as~~ Matter entrainment and ~~gas~~ shocks ~~shocking~~ may are be important factors for determining true kinetic jet power for PC systems.

With tighter, self-consistent observational constraints on the $P_{\rm jet}$-$L_{\rm radio}$ relation across several decades in both parameters, and host system mass, the need for calculating jet kinetic power using model-dependant formalisms (*i.e.* Q) has weakened significantly. Using $P_{\rm jet}$-$L_{\rm radio}$ as an aide, a better understanding of the supermassive black hole power plants which underlie AGN activity can be undertaken. Moreover, future AGN feedback models, when used in simulations, must replicate the observed ~~radio-mode~~ relations studied here. ??

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REFERENCES

Akritas, M. G., & Bershady, M. A. 1996, ApJ, 470, 706 3

Baldi, A., Forman, W., Jones, C., Kraft, R., Nulsen, P., Churazov, E., David, L., & Giacintucci, S. 2009, ArXiv e-prints: 0909.2942 4

Begelman, M. C., & Cioffi, D. F. 1989, ApJ, 345, L21 3

Best, P. N., Kauffmann, G., Heckman, T. M., Brinchmann, J., Charlot, S., Ivezić, Ž., & White, S. D. M. 2005, MNRAS, 362, 25 1

Best, P. N., von der Linden, A., Kauffmann, G., Heckman, T. M., & Kaiser, C. R. 2007, MNRAS, 379, 894 5

Beuing, J., Dobereiner, S., Bohringer, H., & Bender, R. 1999, MNRAS, 302, 209 2

Birkinshaw, M., & Davies, R. L. 1985, ApJ, 291, 32 4

Bîrzan, L., McNamara, B. R., Nulsen, P. E. J., Carilli, C. L., & Wise, M. W. 2008, ApJ, 686, 859 1, 2, 4

—. 2009, ApJ 3

Bîrzan, L., Rafferty, D. A., McNamara, B. R., Nulsen, P. E. J., & Wise, M. W. 2009, ArXiv e-prints: 0909.0397 1

Bîrzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800 1

Blandford, R. D., & Konigl, A. 1979, ApJ, 232, 34 1, 3

Blandford, R. D., & Rees, M. J. 1974, MNRAS, 169, 395 3

Bock, D. C.-J., Large, M. I., & Sadler, E. M. 1999, AJ, 117, 1578 2

Bower, R. G., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2006, MNRAS, 370, 645 1

Bridle, A. H., Davis, M. M., Fomalont, E. B., Willis, A. G., & Strom, R. G. 1979, ApJ, 228, L9 4

Carvalho, J. C., & O'Dea, C. P. 2002a, ApJS, 141, 337 3

—. 2002b, ApJS, 141, 371 3

Cattaneo, A., & Best, P. N. 2009, MNRAS, 395, 518 5

Cavagnolo, K. W., Donahue, M., Voit, G. M., & Sun, M. 2008, ApJ, 683, L107 1

—. 2009, ApJS, 182, 12 1

Cavaliere, A., & Fusco-Femiano, R. 1978, A&A, 70, 677 4

Condon, J. J. 1992, ARA&A, 30, 575 2

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693 2

Croston, J. H., Hardcastle, M. J., Birkinshaw, M., Worrall, D. M., & Laing, R. A. 2008a, MNRAS, 386, 1709 4, 8

Croston, J. H., Hardcastle, M. J., Kharb, P., Kraft, R. P., & Hota, A. 2008b, ApJ, 688, 190 4

Croston, J. H., Kraft, R. P., & Hardcastle, M. J. 2007, ApJ, 660, 191 4

Croston, J. H., Kraft, R. P., Hardcastle, M. J., Birkinshaw, M., Worrall, D. M., Nulsen, P. E. J., Penna, R. F., Sivakoff, G. R., Jordán, A., Brassington, N. J., Evans, D. A., Forman, W. R., Gilfanov, M., Goodger, J. L., Harris, W. E., Jones, C., Juett, A. M., Murray, S. S., Raychaudhury, S., Sarazin, C. L., Voss, R., & Woodley, K. A. 2009, MNRAS, 395, 1999 4

Croton, D. J., Springel, V., White, S. D. M., De Lucia, G., Frenk, C. S., Gao, L., Jenkins, A., Kauffmann, G., Navarro, J. F., & Yoshida, N. 2006, MNRAS, 365, 11 1

De Young, D. S. 2006, ApJ, 648, 200 4

De Young, D. S., O'Neill, S. M., & Jones, T. W. 2008, in Astronomical Society of the Pacific Conference Series, Vol. 386, Extragalactic Jets: Theory and Observation from Radio to Gamma Ray, ed. T. A. Rector & D. S. De Young, 343–+ 1

Dunn, R. J. H., & Fabian, A. C. 2008, MNRAS, 385, 757 1

Dunn, R. J. H., Fabian, A. C., & Celotti, A. 2006, MNRAS, 372, 1741 4

Dunn, R. J. H., Fabian, A. C., & Taylor, G. B. 2005, MNRAS, 364, 1343 1, 4

Fabian, A. C., Sanders, J. S., Ettori, S., Taylor, G. B., Allen, S. W., Crawford, C. S., Iwasawa, K., Johnstone, R. M., & Ogle, P. M. 2000, MNRAS, 318, L65 1