Ram pressure statistics in the MareNostrum Galaxy Simulation.

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Abstract. Bent tail radio sources (BTRSs) have already been successfully used as tracers of galaxy clusters for redshifts of up to ≈ 1. Within the sample of known BTRSs, 60% are found in rich clusters while 40% exist in poor clusters. The bent morphology is believed to be caused by the ram pressure resulting from the interaction of the galaxy jets with the intracluster medium. In this paper we use the MareNostrum Universe Simulation to investigate the likelihood of finding a BTRS in a poor cluster as compared to a rich cluster. The question of where BTRSs are found and how those environments contribute to their optical and radio morphology gives us insight into the correlations between optical properties and radio properties and how they can be used to improve the efficiency of using BTRSs as tracers of galaxy clusters at high redshift.

1. Introduction.

It is widely accepted that supermassive black holes (SMBH) lie at the heart of all massive galaxies (Kormendy & Richstone, 1995)[0]. Elliptical galaxies dominate the high mass end of the galaxy mass function. Kauffmann et. al., (2003)[0] found that the fraction of Active Galactic Nuclei (AGN) in the nearby Universe grows steadily from 10% for galaxies with stellar mass of $10^{10} M_{\odot}$ to about 80% for $10^{11} M_{\odot}$ galaxies. It flattens out at about 100% for masses greater than $10^{12} M_{\odot}$.

The prevalence of radio-loud galaxies on the other hand was found to rise steeply from 0.01% for stellar masses of $3 \times 10^{10} M_{\odot}$ to about 30% for $5 \times 10^{11} M_{\odot}$. AGN are believed to be powered by the accretion of the inter-stellar medium (ISM) onto the central SMBH. A tight correlation was found between bulge luminosity and the mass of the SMBH Ferraresse, (2002) [**?**]. This correlation was found to be independent of galaxy type. The optical properties of radio-loud ellipticals are indistinguishable from those of radio-quiet ellipticals (Kormendy & Djorgovski, 1989)[0]. Double lobe radio galaxies were observed to have two different morphologies by Fanaroff & Riley (1974) [0] and a dividing line of the two morphologies was later found to be at the radio power of $P_{1440} < 5 \times 10^{25} WHz^{1}$, assuming a spectral index of $\alpha = 0.8$: where FR-IIs are generally found above that line while FR-Is generally lie below. FR-I galaxies are edge-darkened with the highest radio surface brightness along the jet close to the host galaxy and FR-II galaxies are edge brightened with the highest radio surface brightness at the outer edges of the jet plumes Fanaroff & Riley (1974) [0]. Both types of Fanaroff-Riley galaxies (FRGs) show evidence of relativistic jets emanating from their hosts. Due to projection effects and other biases, it is not easy to constrain the number of AGN that are BTRS. Blanton (2000)[0] used the First survey results to count the number of BTRS and found the total number of BTRSs to be about half the number found using automatic source finding methods.

1.1. Radio properties of bent tail galaxies.
O'Donaghue et. al., (1993) [**?**] list the following general properties for Wide Angle Tail radio galaxies (WATs):

- An association with a dominant galaxy in the center of a galaxy cluster.
- A large linear size extending more than 50 kpc from the radio core.
- A dramatic jet-hot spot transition.
- A C-shape caused by large-scale bends of both tails in the same direction.
- Radio power within a factor of 3 the FR I-II break or less.
- They are not found in clusters with strong cooling cores; the radio sources associated with the central galaxies in these clusters are smaller and fainter.

1.2. Optical properties of bent tail galaxies.
The sizes of the BTRSs have a non-Gaussian distribution. They can have a linear size of tens of kiloparsecs or be as large as a megaparsec. The properties of the hosts of these galaxies were found to be ellipticals whose structure showed no significant deviation from the structure of 'normal' elliptical galaxies (Blanton, 2000)[0].

Ledlow[0] found that the Fanaroff-Riley radio galaxies are ellipticals showing some substructure at the sub-kiloparsec level. They also found that, except for their size, these hosts are indistinguishable from ordinary elliptical galaxies. This led them to conclude that, due to the presence of the SMBH in their cores, all ellipticals display jets at some or other stage in their evolution. They also had magnitudes that are brighter than -21 mag and 95% of their sample were FR I galaxies. Blanton (2000) found 80% of her sample to be FR I galaxies. [0] found that the mean V-magnitudes of her whole sample of radio galaxies was -22.658 with $\sigma \leq 0.682$ and for the brightest cluster galaxies of her sample the mean was -23.213 with $\sigma \leq 0.366$. These magnitudes correspond to the brighter end of the elliptical galaxy luminosity function. [0] found the distribution of elliptical galaxies to be Gaussian peaking around -18 magnitude in the V-band. [0] found the M/L ratio of radio-loud galaxies to be higher than normal ellipticals. So these radio galaxies are usually the most massive galaxies in the universe.

2. Simulation and methodology.
This simulation, done on the MareNostrum supercomputer in Barcelona, is described in detail by Gottlöber et. al. (2006)[0]. It uses the entropy conserving GADGET-2 code [0] to follow the non-linear evolution of the gas and dark matter cosmic density fields from z=40 to the present epoch. It employs the spatially flat concordance model with the following parameters: $\Omega_m = 0.3, \Omega_\Lambda = 0.7, \Omega_b = 0.045, \sigma_8 = 0.9, h = 0.7$ within a co-moving box with $500h^{-1}$ Mpc sides. It models both dark matter and gas components using 1024^3 particles per species. The mass of each gas particle is $1.5 \times 10^9 h^{-1} M_\odot$ and the mass of each dark matter particle is $8.3 \times 10^9 h^{-1} M_\odot$. The equations of gas dynamics were solved adiabatically using SPH by excluding radiative processes or star formation.

We use the results of the Marenostrum Universe Simulation at the present epoch to investigate the presence of massive galaxies and their environments. The presence of a dark matter overdensity is used as a tracer of galaxy halo existence. We employ the hierarchical friends of friends (HFOF) algorithm (Klypin et. al., 1999)[0] with progressively shorter linking lengths of $b_n = \frac{b}{2^n}$ with $n = 0, 1, 2, 3$ to separate clusters, subclusters, cluster cores and galaxies. A linking length of $b_n = 0.17$ times the mean particle separation corresponds to the virial overdensity, where we can separate clusters from voids (Gottlöber et. al., 2006)[0].We use $n = 3$ for a galaxy to get $b_n = 0.02125$ which is 512 times the mean density for a cluster. We apply this to any overdensity of 50 dark matter particles or more for a galaxy.

2.1. Methodology.
Narrow angle tail galaxies (NATs) have long been believed to be a product of the ram pressure experienced by the galaxy moving through the Intra-Cluster Medium (ICM) (Miley et. al., 1972)[0]. This mechanism did not adequately address the morphology of Wide-Angle Tail galaxies (WATs), because they are usually associated with the brightest cluster galaxy (BCG) (O'Donaghue et. al., 1993)[**?**]. The BCG is always located near the center of the cluster [0] and as a result its velocity relative to the ICM is insufficient for ram pressure to be the cause of the bent morphology. Venkatesan, (1994)[**?**] showed that the velocity of the host galaxy with respect to the ICM should of the order 1000 kms^{-1} for ram pressure to be the cause of the bent tail morphology.
The ICM in poor clusters has density range of $10^{-5}\mathrm{cm}^{-3} \leq \mathrm{n_e} \leq 10^{-4}\mathrm{cm}^{-3}$ (Pisano et. al., 2004)[0] and a temperature $10^5\mathrm{K} \leq \mathrm{T} \leq 10^7\mathrm{K}$ (Davé et. al. 2001)[**?**] while the ICM in rich clusters has a density range of $10^{-3}\mathrm{cm}^{-3} \leq \mathrm{n_e} \leq 10^{-2}\mathrm{cm}^{-3}$ and a temperature $10^7\mathrm{K} \leq \mathrm{T} \leq 10^8\mathrm{K}$.

For FR I galaxies, the average jet velocity $\beta = \frac{v}{c}$ was found to be $0.54c \pm 0.03$, where the jets flare (Arshakian & Longair, 2004)[0]. Analysing different samples and using different methods of analysis, the jet speed for FR II galaxies was found to vary between $0.5c \leq v \leq 0.7c$ (Wardle & Aaron 1997[0], Arshakian & Longair 2004[0]).
For the jets of AGN to be visibly bent, the ram pressure caused by the jet on the ambient medium must be of the same order of magnitude as the ram pressure caused by the motion of the galaxy through the ambient medium. This also takes into account the radius of curvature that the jet has to have for it to be discernibly bent.
The bending equation,

$$\frac{\rho_{jet} v_{jet}^2}{R} = \frac{\rho_{ext} v_{gal}^2}{h} \tag{1}$$

where h is the cylindrical radius of the jet and R is the radius of curvature of the jet, is used to calculate the balance of forces for jets bent by ram pressure from the ambient medium. The values ρ_{jet}, ρ_{ext}, v_{jet} & v_{gal} denote the density within the jet, the density of the ambient medium, the jet speed and the velocity of the galaxy relative to the ambient medium. O'Dea & Owen (1985)[0] calculated a mean relative velocity of $\approx$ 547 $\mathrm{km.s}^{-1}$ for NAT galaxies in rich clusters. Jetha et. al., (2006)[0], using the bending equation, with h=1 kpc, R=20 kpc, $\rho_{\mathrm{jet}} = 1.5 \times 10^{-3}\mathrm{cm}^{-3}$ found the galaxy velocities needed to achieve bent morphology to be $\approx 870\mathrm{km.s}^{-1}$ for WAT galaxies.

We use an analysis that would allow us to find one number that may be used to extract data from simulation, by modifying the analysis pioneered by Zaninetti (2007)[0]. We adopt the average number density $6.74 \times 10^{-3}\text{cm}^{-3}$ used by Zaninetti (2007)[0], to calculate the average density of the jet. We write this as a ratio of the critical density of the universe as $\eta = \frac{\rho_{\text{jet}}}{\rho_{\text{crit}}}$, where we use the WMAP Baryon density $\rho_{\text{crit}} = 0.25\text{m}^{-3} \pm 0.01$)(Bennett et. a., 2003)[0]. We get a dimensionless number $\eta = 26960$

We shall also use the average velocity of the jet $v_{\text{jet}} = 0.008\text{c}$ since the density is the average value along the whole jet (Zaninetti, 2007)[0]. We define the dimensionless constants $\zeta = \frac{R}{h} = 100$ and $\eta = \frac{\rho_{\text{jet}}}{\rho_{\text{crit}}}$ and we rearrange our bending equation to be:

$$\rho_{\text{ext}} v_{\text{gal}}^2 = \frac{\eta}{\zeta} \times (0.008\text{c})^2 \tag{2}$$

where $\eta = 26960$

$$\rho_{\text{ext}} v_{\text{gal}}^2 = \eta\zeta \times (0.008\text{c})^2 = 1.725 \times 10^{-2}\text{c}^2 \tag{3}$$

$$\rho_{\text{ext}} v_{\text{gal}}^2 = 1.553 \times 10^9 \tag{4}$$

where ρ_{ext} is stated as a ratio of the ICM density divided by the critical density of the universe. This allows us to extract these number directly from the simulation by calculating the average velocity of the dark matter particles that form the galaxy. By also using the average velocity of the gas particles that lay within a 150 kpc radius of the core of the galaxy, we can calculate the velocity of the galaxy with respect to the surounding gas. This makes it easy to compare that calculation to a single number to quantify the environment. We choose a galaxy core to be made of 50 dark matter particles. This corresponds to a mass of $4.15 \times 10^{11} M_\odot$. This mass has both a good resolution in the simulation and corresponds to galaxy masses where between 80 % and 100% of the galaxies are AGN.

The simulation provides velocity and position for each of the gas and dark matter particles. We use these to calculate the average density, the average velocity and position of gas particles in displacement bins of 0.1dex.

3. Results

3.1. Dependence on cluster mass.

Figure 1 shows the fraction of galaxies that have relative velocities that are above 1000 km/s as a function of the mass of the host cluster, we see an exponential increase from 0.01 at $10^{13.8} M_\odot$ to 0.43 for $10^{15.2} M_\odot$. There is a small fraction of clusters whose mass is less than $10^{13.8} M_\odot$ that host high velocity galaxies. It is an expected result since the galaxies' kinetic energy is largely produced by the gravitational potential well of the host cluster. The high mass clusters do show more capacity to produce high velocity galaxies. Galaxies that are closer to the clusters' centre of gravity are expected to have lower relative velocities and that would be one of the reasons why the fraction of high velocity galaxies is not higher at the high mass end of the clusters.

3.2. Statistics of galaxies with the critical ram pressure.

Using the definition for circular velocity $v_{\text{circ}}(\text{r}) = \sqrt{\frac{\text{GM(r)}}{\text{r}}}$ where the masses of of the halos with high enough ram pressure for jet bending span more than 5 orders of magnitude in mass (about 500 km/s in circular velocity). The number of potential BTRS is 3590 galaxies with masses higher than $4.15 \times 10^{11} M_\odot$ is shown in figure 2(a) using the detailed analysis of Zaninetti (2007). Using the Venkatesan (1994) result of 1000 km/s figure 2(b) that the potential BTRS are 887 galaxies at $z = 0$. We also find the mean cluster mass that hosts potential BTRS to lie in the $10^{14.5} M_\odot$ mass bin. This tells us that there is equal probability of finding BTRS in poor and in rich clusters. We also see that the number of potential BTRS falls sharply for cluster masses lower than $10^{13.8} M_\odot$. When comparing figure 2(a) and figure 2(b) we see that the density of the environment of the galaxy plays as important a role as the velocity of the galaxy. Most of the galaxies in figure 2(a) have a velocity lower than 1000 kms^{-1}.

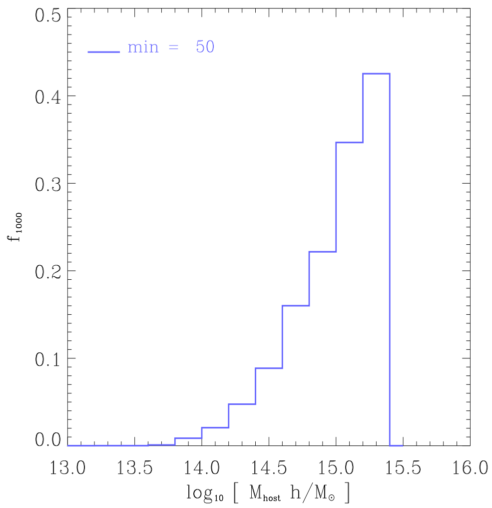

Figure 1. The ratio of galaxies whose velocity relative to the ambient gas (ICM) is $\leq 1000 kms^{-1}$ as a function of the mass of the host cluster. The high mass end of the histogram is limited by the highest mass cluster in the simulation.

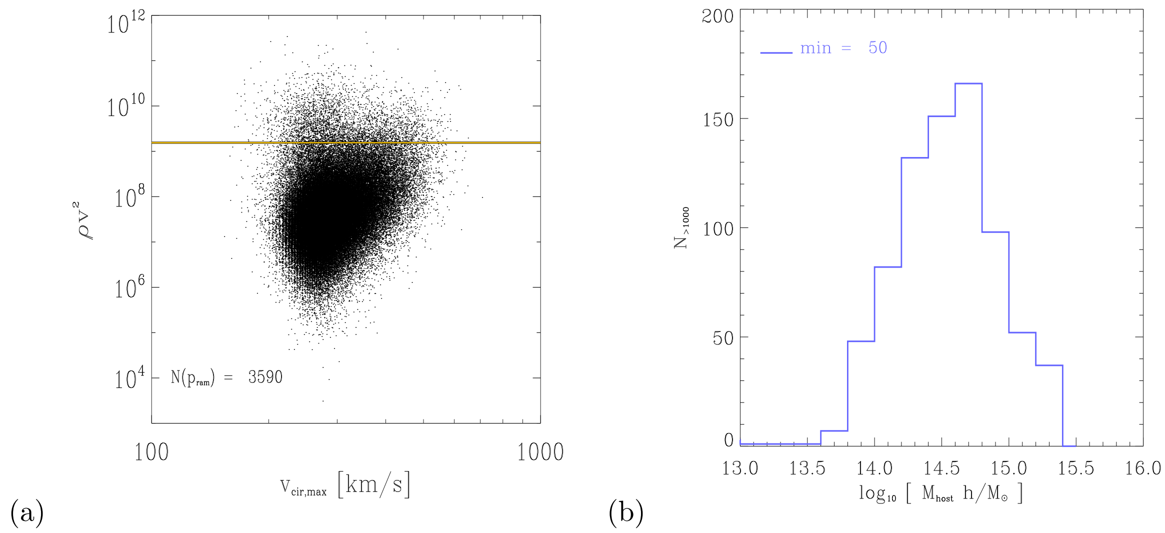

Figure 2. Results of the number of galaxies that qualify as potential BTRSs by the ram pressure bending method (a). The number of galaxies whose velocity relative to the ambient gas (ICM) is $\leq 1000 kms^{-1}$ (b) is 887 in total. The median mass of the host cluster is $10^{14.5} M_\odot$
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4. Conclusion.

Using the results from the MareNostrum Universe Simulation we found that there should be equal probability of finding BTRS in clusters of mass greater than $10^{14.5} M_\odot$ and clusters that have mass that is less than this. Since lower mass clusters are more prevalent than the highest mass clusters in the simulation, We note that at the high mass end, there is an upper limit to cluster mass. There is also a lower mass limit of $10^{13.8} M_\odot$ for the existence of BTRS, beneath which there is not an appreciable number of potential BTRS that may form. The lower mass limit corresponds to the cluster mass where both the fraction of galaxies with relative velocities greater than 1000 km/s and their number density falls approach zero. The high mass limit corresponds to where we find the most massive cluster in the simulation. We cannot quite compare the number densities of potential BTRS to observations without making assumptions about the lifetimes of AGN activity and to a lesser extent viewing angles of galaxy jets in the universe.

Most of the galaxies that are potential BTRSs have a relative velocity that is less than 1000 kms^{-1} and this requires further investigation to separate the effect of a much denser environment from the effect merging clusters.

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