Dynamical friction of radio galaxies in galaxy clusters

Biman B. Nath
Raman Research Institute, Sadashivanagar, Bangalore 560080, India

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ABSTRACT
The distribution of luminous radio galaxies in galaxy clusters has been observed to be concentrated in the inner region. We consider the role of dynamical friction of massive galaxies ($M \sim 10^{12.5} M_{\odot}$), assuming them to be hosts of luminous radio galaxies, and show that beginning with a Navarro–Frenk–White density profile of a cluster of mass $M_{200} \sim 10^{15} M_{\odot}$ of concentration $c \sim 5$ and collapsing at $z \sim 1$, the density profile of radio galaxies evolves to a profile of concentration $c \sim 25$, as observed, in a time-scale of $t \sim 3$–$5$ Gyr.

Key words: galaxies: active – galaxies: clusters: general – radio continuum: galaxies.

1 INTRODUCTION
Recent observations have shown that powerful radio sources in galaxy clusters are concentrated towards the cluster centre. In a survey of 30 clusters of galaxies, Morrison & Owen (2003) found that the spatial distribution of high-luminosity radio galaxies in rich clusters is described by a small core radius. In particular, they found that the spatial distribution of galaxies depends on their radio power – high-luminosity radio galaxies have a smaller core radius ($\sim 0.12 \pm 0.02$ Mpc) than low luminosity ones ($\sim 0.4 \pm 0.08$ Mpc). Recently, Lin & Mohr (2007) have collected data for 188 rich clusters, and they have analysed the spatial distribution of radio galaxies contained within them. They found that the spatial distribution of powerful radio sources could be fit by the ‘universal’ Navarro–Frenk–White (NFW) profile (Navarro, Frenk & White 1996) with a larger concentration parameter than needed for fitting the total mass distribution of the cluster, and similar to the findings to Morrison & Owen (2003), they discovered that the concentration of galaxies in the spatial distribution increased with their radio power.

Many explanations can be put forward for such a steep spatial distribution of radio galaxies in clusters. It is possible that the increased number density of galaxies in the inner region facilitates mergers and interactions that can trigger active galactic phenomena and increase the radio luminosity of galaxies. Also, radio galaxies are mostly associated with giant ellipticals which generally inhabit the central regions of rich clusters. Moreover, the increased pressure of the hot X-ray gas of rich clusters in the inner region may enhance the radio luminosity of FR II radio galaxies by confining the lobes with high pressure.

There is also a dynamical aspect of the problem besides these factors. If the hosts of radio-loud objects, are massive galaxies, then dynamical friction will lead to mass segregation in galaxy clusters, and radio galaxies will settle towards the cluster centre over many orbits. The situation is analogous to the phenomenon of large density of millisecond pulsars in the central regions of globular clusters. This concentration is believed to be due to favourable conditions in the cluster core for accretion spin-up of neutron stars leading to the phenomenon of millisecond pulsars. However, it is the first process of mass segregation in globular clusters owing to dynamical friction that makes massive stars settle towards the centre thereby leading to an increased number density of neutron stars in the inner regions (Meylan & Heggie 1997).

Mass segregation by the process of dynamical friction is also expected to occur in galaxy clusters and it will lead to a preponderance of massive galaxies towards the cluster centre. This process is likely to occur simultaneously with other processes of galactic evolution that may make galaxies in the inner region prone to becoming a radio-loud source. To study the dynamical aspect of the evolution of spatial distribution of radio sources, one would need to isolate it from other evolutionary process and determine if it is a significant process by itself. We wish to address this issue in this paper.

The main motivation to isolate the dynamical aspect of the problem comes from the fact that the hosts of radio galaxies are often massive galaxies, irrespective of their membership in clusters or groups of galaxies. Recent statistical studies of radio-loud objects show that their hosts are predominantly massive objects (containing black holes of mass $\sim 10^8 M_{\odot}$) (Best et al. 2005). It is therefore reasonable to expect that dynamical evolution of massive galaxies in clusters will have a significant effect on the spatial distribution of radio-loud sources in galaxy clusters, irrespective of other processes that contribute towards increasing the radio output of a galaxy.

Here, we focus on the dynamical evolution of the distribution of massive galaxies in clusters from dynamical friction, and compare with recent observations.

2 HOSTS OF RADIO GALAXIES
Powerful radio sources (with $P_{1.4 \text{GHz}} \geq 10^{24}$ W Hz$^{-1}$) have been found to be associated with giant ellipticals, the oldest and the most massive galaxies in the universe. Best et al. (2005) have discussed the mass dependence of radio activity with the help of a statistical
analysis of the radio properties of galaxies from the 2dF survey. They have shown that the probability of a galaxy containing a central black hole of a certain mass to have a given (or larger) radio luminosity depends strongly on the black hole mass; the probability scales as \( \propto M_{BH}^{1.6} \). The (volume-weighted) distribution of the black hole mass in the sample showed that most radio-loud objects had a black hole mass in the range \( M_{BH} \sim 10^{-6} - 10^{5} M_\odot \), peaking at \( M_{BH} \sim 10^{5} M_\odot \). The total mass of the host galaxy of radio-loud sources is related to the central black hole mass. Fine et al. (2006) found from the analysis of the 2dF QSO survey that for a quasi-stellar object host, containing a central black hole of mass \( M_{BH} \sim 10^{5.4} M_\odot \), the total dark matter mass of the host galaxy is \( \sim 10^{12.5} M_\odot \).

Based on these considerations, we will consider galaxies of total (dark matter) mass \( \sim 10^{12.5} M_\odot \), and containing a central black hole of mass \( M_{BH} \sim 10^{5.5} M_\odot \), as examples of host galaxies of radio-loud objects in our calculation below.

### 3 DYNAMICAL FRICTION

Consider a galaxy cluster of total mass \( M_c \) and velocity dispersion \( \sigma \). We assume that the average mass distribution inside the cluster follows the NFW profile (Navarro, Frenk & White 1997), \( \rho = \rho_c \left( \frac{r}{r_s} \right)^{-2} \left[ 1 + \left( \frac{r}{r_s} \right) \right]^{-1} \) where \( r_s = r_{vir} / c, c \) is the concentration parameter and \( r_{vir} \) is the virial radius. The virial radius is fixed by the overdensity estimated from spherical collapse model, which is approximately \( \Delta (z = 0) \sim 100 \) at the present epoch, for the standard \( \Lambda \) cold dark matter cosmological model (\( \Omega_m = 0.3, \Omega_\Lambda = 1 - \Omega_m \)) (see e.g. Komatsu & Seljak). The characteristic density \( \rho_c \) is then given by

\[
\rho_c = \frac{c^3}{3} \ln(1+c) - \frac{c}{1+c},
\]

where \( \rho_c(z) \) is the critical density of the universe at redshift \( z \). For a large range of length-scales (barring the central and the outer regions of the cluster), the mass density \( \rho \propto r^{-2} \). The mass distribution in these parts will be characterized by a near constant velocity dispersion \( \sigma \).

We assume a concentration parameter \( c = 5 \) for a rich cluster as suggested by N-body simulations (Navarro, Frenk & White 1996). We also assume a Maxwellian distribution of velocities of objects in the clusters with dispersion \( \sigma \), and assume the average mass of galaxies to be \( m \).

Consider the motion of a massive galaxy of mass \( M \) and speed \( V \) in this cluster. Its motion in the background potential of numerous small galaxies of mass \( m \), will be perturbed by random interactions with these galaxies. These perturbations will amount to a force of dynamical friction given by

\[
F_{\text{drag}}(r) = -\frac{4\pi G^2 M n m \ln \Lambda}{V^2} \left[ \text{erf}(X) - \frac{2X}{\sqrt{\pi}} \exp(-X^2) \right],
\]

where \( n \) is the number density of galaxies of mass \( m \) and \( X = V / \sqrt{2} \sigma \). The dynamical friction will slowly change its orbital parameters and the massive galaxy will slowly settle towards the cluster centre over many orbits.

Consider a near circular orbit of the massive galaxy. Then, for a large range of length-scales in the cluster, we have \( V = \sqrt{\Delta} \) and \( X = 1 \). The coulomb logarithm is approximately \( \ln \Lambda \sim \ln \frac{b_{\text{max}} V}{R_{\text{clus}}} \) (Binney & Tremaine 1987, equation 7-13b). For \( M \sim 10^{12.5} M_\odot \) and \( V \sim 1300 \text{ km s}^{-1} \) (see below for the choice of this value), we have \( \ln \Lambda \sim \ln \frac{b_{\text{max}}}{R_{\text{clus}}} \). If we take \( b_{\text{max}} \) as the cluster core radius which is \( \sim 100 \text{ kpc} \) for rich clusters, then \( \ln \Lambda \sim 2.5 \). In this case, the product \( \left[ \text{erf}(X) - \frac{2X}{\sqrt{\pi}} \exp(-X^2) \right] \ln \Lambda \sim 1.1 \) and we assume it to be unity for simplicity. Also, we will use the average density of matter \( \rho = nm \) in the above expression.

If we consider an inspiraling orbit of a massive galaxy owing to the dynamical friction from its interactions with average mass galaxies, then one can estimate the time-scale over which the distance of the massive galaxy from the cluster centre would significantly decrease. Since the angular momentum \( L \sim MVr \) changes according to \( dL/dr = F_{\text{drag}} \times r \), we have

\[
\frac{1}{r} \frac{dr}{dt} = -\frac{4\pi G^2 M \rho}{V^3},
\]

since the circular velocity \( V \) changes a little in the region of the cluster potential under consideration (where \( \rho \propto r^{-2} \) and the circular velocity \( V = \sqrt{\Delta} \)). Ostriker & Turner (1979) also used this equation to study dynamical friction in galaxy clusters (see also Nusser & Sheth 1999).

We can estimate the time-scale of dynamical friction as \( t_{\text{dyn}} \equiv \frac{r}{dr/dt} \sim \frac{1}{4\pi G^2 M \rho} \frac{1}{V^3} \). For \( V \sim 10^3 \text{ km s}^{-1}, M \sim 10^{12.5} M_\odot \), and using the matter density at the characteristic radius \( r_c \) (using equation 1), \( \rho_c \sim 10^{-26.6} \text{ g cm}^{-3} \), for \( c = 5 \) and \( z = 0 \), we have

\[
t_{\text{dyn}} \sim 2.4 \text{ Gyr} \left( \frac{V}{10^3 \text{ km s}^{-1}} \right)^3 \left( \frac{M}{10^{12.5} M_\odot} \right)^{-1} \left( \frac{\rho}{10^{-26.6} \text{ g cm}^{-3}} \right)^{-1}.
\]

It is believed that rich clusters formed at \( z \sim 1 \), judging from the lack of evolution in X-ray luminosity function of clusters up to \( z \sim 1 \) (see e.g. Rosati, Borgani & Norman 2002). The mass distribution would have settled into a NFW profile by that epoch. If such a cluster contained a few massive galaxies far from its centre, then the above estimate shows that these massive galaxies would have spiralled towards the cluster centre in a few Gyr time-scale.

The time evolution of the orbit of a massive galaxy embedded in a galaxy cluster can be obtained from numerically solving equation (3). A few representative cases are shown in Fig. 1 for

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**Figure 1.** The evolution of orbit for a massive galaxy (\( M = 3 \times 10^{12} \)) embedded in a rich cluster (\( M_\Delta = 10^{15} M_\odot \)) is shown for a few initial radii.
$M = 10^{12.5} \, M_\odot$, $V = 10^3 \, \text{km s}^{-1}$. We compute the density distribution of the cluster halo for $M_d = 10^{15} \, M_\odot$ collapsing at $z = 1$. We emphasize that the results shown in Fig. 1 are approximate and are based on several assumptions. First, we have assumed circular orbit. But the results shown in Fig. 1 can be interpreted as the evolution of the radial distance averaged over an orbital period. Also, we have neglected the effect of the massive galaxy being an extended object. In reality, the galaxy will be tidally stripped, decreasing its mass, as it spirals inward (see Nusser & Sheth 1999 for a discussion on this effect).

We can then ask how the distribution of such massive galaxies would evolve in a statistical sense, beginning with the NFW profile of a given concentration parameter. A given cluster will contain only a handful of massive galaxies, but we can consider a statistical ensemble of clusters with the same concentration parameter and total mass, which will contain several massive galaxies with initial orbital parameters such that the total mass distribution of the ensemble resembles a NFW profile of the assumed concentration parameter (here $c = 5$). Slowly, over time and many orbits, the massive galaxies will settle towards the centre, and their mass distribution will change.

To estimate the gradual change in the mass distribution of massive galaxies immersed in a gravitational potential determined by several average mass galaxies, we divide the cluster into several annuli, and compute the cluster halo density in the $i$th annulus, $N_M(i, t = 0)$, so that the density profile of these galaxies $[N_M(i, t = 0)/\text{vol}(i)]$, where $\text{vol}(i)$ is the volume of the $i$th annulus] follows the NFW profile with same concentration ($c = 5$ here). We normalize the number of massive galaxies in different annuli by the density at the outermost annulus, which does not change owing to negligible dynamical friction at that radius.

We first calculate the change in radius of these massive galaxies initially stationed at each annulus using equation (3). We compute their radii after an elapsed time interval, and then we recalculate the number of massive galaxies in all annuli $N_M(i, t \geq 0)$, again normalized by the number of massive galaxies in the outermost annulus. From this, we calculate the number density of massive galaxies in each annulus as a function of time. The result will depend on the mass assumed for the massive galaxies and the time elapsed. Our previous estimates show that we can expect a significant evolution in the distribution of massive galaxies over a time-scale of a few Gyr for galaxies with $M \sim 10^{12.5} \, M_\odot$.

We consider a cluster of mass $M_d = 10^{15} \, M_\odot$ and concentration parameter $c = 5$. The virial radius for a cluster collapsing at $z \sim 1$ is calculated to be $r_{200} \sim 2.6 \, \text{Mpc}$. The appropriate velocity dispersion for such a cluster is taken from the scaling observed in simulations by Evrard et al. (2008) to be $\sigma \sim 9.5 \times 10^3 \, \text{cm s}^{-1}$ (for Hubble constant $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$); we assume it to be independent of location inside the cluster, we consider massive galaxies with $M \sim 10^{12.5} \, M_\odot$ and $V = \sqrt{2} \sigma \sim 1.3 \times 10^8 \, \text{cm s}^{-1}$.

4 RESULTS

We show in Fig. 2 the initial mass distribution by dotted line; it is a NFW mass profile with $c = 5$ for $M_d = 10^{15} \, M_\odot$ collapsing at $z = 1$. We plot the radius as a fraction of $r_{200}$. Then, the mass distribution of an ensemble of galaxies with $M = 3 \times 10^{12} \, M_\odot$ is shown after $t = 1.5, 3$ and $5 \, \text{Gyr}$ with solid lines. It is found that the distribution steepens with time. The distribution at outer radii does change much, but massive galaxies in the middle region settle towards the centre, increasing the density of these galaxies in the bins of radii in these regions. The dashed line shows a NFW profile with $c = 25$ All profiles have been drawn keeping the mass density at the outermost bin fixed in time, for comparison.

We therefore find that the distribution of massive galaxies in a statistical ensemble of clusters steepens with time. The steepening depends on the assumed mass of the massive galaxies and the time elapsed. In our fiducial case of $M = 3 \times 10^{12} \, M_\odot$ immersed in a cluster of total mass $M_d + 10^{15} \, M_\odot$ collapsing at $z = 1$, we find that a distribution with initial $c = 5$ has changed to a distribution with $c = 25$ over a time-scale $t \sim 3$–$5 \, \text{Gyr}$.

It is interesting to compare this time-scale with the cosmological lookback time. The lookback time to redshift $z \sim 0.5$ is $t \sim 4 \, \text{Gyr}$. If rich clusters formed at these redshifts, then their mass distribution would have settled into the NFW profile by that epoch. If such a cluster contained a few massive galaxies far from its centre, then it is conceivable that these massive galaxies would have spiralled towards the cluster centre by the present epoch.

5 DISCUSSIONS

Lin & Mohr (2007) have stacked the data from 188 clusters containing 16 646 radio-loud objects (with radio luminosity $P > 10^{23} \, \text{W Hz}^{-1}$) to produce the density profile of these objects. The number of radio-loud objects within the radius $r_{200}$ in their study was 836. They found that the density profile corresponds to a NFW profile with $c = 25 \pm 7$, excluding the brightest cluster galaxy (BCG). With the inclusion of BCGs which they defined as radio-loud objects within $0.1 \, r_{200}$, the profile steepens to $c \sim 52_{-14}^{+25}$.

The solid curve in Fig. 2 steepens further below a radius $0.1r_{200}$, and excluding this part (equivalent to excluding the statistics of BCGs), we find that the density distribution is comparable to a NFW profile with $c \sim 25$, close to the observed value. It then appears the...
distribution of radio-loud objects in the ensemble cluster (produced
by stacking the data of numerous clusters) can be explained by
assuming that the original mass distribution was a standard NFW
profile with $c \sim 5$, and that massive galaxies slowly sink towards
the cluster centre owing to dynamical friction. The time taken to match
the observed distribution is $t \sim 3\text{--}5\text{ Gyr}$ if the massive galaxies have
$M \sim 10^{12.5}\,\text{M}_\odot$, and belonging to a cluster of $M_\text{cl} = 10^{15}\,\text{M}_\odot$.

It is interesting to note that Lin & Mohr (2007) have found that
more powerful radio sources are more centrally concentrated than
the weaker ones. For example, they found that radio sources with
luminosity larger than $10^{24.5}\,\text{W}\,\text{Hz}^{-1}$ have a distribution comparable
to a NFW profile with $c \sim 59 \pm 11$. This trend is expected in the
above scenario if the probability of a galaxy to have a given radio
luminosity increases with its total mass which indeed seems to be the
case. Best et al. (2005) found from the 2dF survey data that the
probability of a galaxy with a black hole mass $M_\text{BH}$ to have radio
power larger than a given value approximately scales as $M_\text{BH}^{1.6}$ If the
central black hole mass scales linearly with the dynamical mass $M_\text{dyn}$
of the host galaxy (e.g. Hopkins et al. 2007), then one expects the
hosts of more powerful radio sources to be more massive galaxies.

We note here that dynamical friction cannot be the complete story
behind the concentration of radio-loud objects in clusters. Masses
of galaxies alone do not determine their radio properties; there are
many factors that contribute to its radio luminosity, like mergers
and interactions with other galaxies, and properties of the medium
confining radio lobes. Here, we have isolated the dynamical aspect
of the issue, and the results show that dynamical friction can also
be as important as other factors in producing a steep density profile
of radio sources in clusters.

6 SUMMARY

We study the dynamical friction of massive galaxies – which can
often be hosts of radio-loud objects – in galaxy clusters, and find
the time-scale of mass segregation to be $t \sim 3\text{--}5\text{ Gyr}$, for galaxies
of mass $\sim 10^{12.5}\,\text{M}_\odot$ within clusters of mass $M_\text{cl} \sim 10^{15}\,\text{M}_\odot$. We
show that this effect can help to explain the observed distribution of
radio-loud objects in rich clusters of galaxies.

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