

## Gas and Galaxy Evolution in Poor Groups of Galaxies

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**Abstract.** Poor groups of galaxies are the repositories of most of the baryons in the local Universe and are environments in which galaxy evolution is likely to be both more recent and simpler than in the cores of rich clusters. Yet we know little about groups outside of our own Local Group. We discuss recent results from optical, X-ray, and radio observations of nearby poor groups that focus on the evolution of gas and galaxies in these common environments.

### 1. Introduction

Poor groups are both typical environments for galaxies and relatively simple environments for galaxy evolution, especially in contrast to the complex mechanisms that might drive galaxy evolution in hotter, denser clusters of galaxies. We define poor groups as systems with five or fewer  $L^*$  or brighter galaxies. Many galaxies, including our own Milky Way, lie in poor groups, which can be roughly divided into three major classes based on their X-ray and galaxy morphologies. The first class includes the NGC 533 group (Figure 1), which is marked by a large fraction of early type galaxies and by luminous, symmetric, diffuse X-ray emission coincident with the central giant elliptical. Groups of the second class are like Hickson Compact Group 90 (Figure 1), which has a lower fraction of early types and an apparently unrelaxed X-ray halo not clearly associated with particular galaxies. In HCG 90, we observe several interacting galaxies in the core instead of a giant elliptical. The third class of poor groups includes our own Local Group, which consists of two giant late type galaxies and their satellite populations apparently falling together for the first time. These groups have few or no early type members, have little or no diffuse X-ray emission, and, while bound, are not necessarily virialized.

A classic problem in the study of poor groups has been that, with five or fewer known members, it is difficult to differentiate true, bound systems from chance superpositions of galaxies along the line-of-sight. Furthermore, even in bound groups, the small number of known members has prevented an accurate calculation of the group kinematics. We use multi-object spectroscopy to determine whether there are members further down the luminosity function and find a surprising result: groups of the first class, those with X-ray luminous halos, can have 50–60 members down to  $M^*+5$  projected within  $\sim 0.5h^{-1}$  Mpc, their virial radii (Figure 2). These newly discovered galaxies confirm such groups as bound systems and provide a means for assessing the group's dynamical state. Groups of the second and third classes, which have at most marginally detected

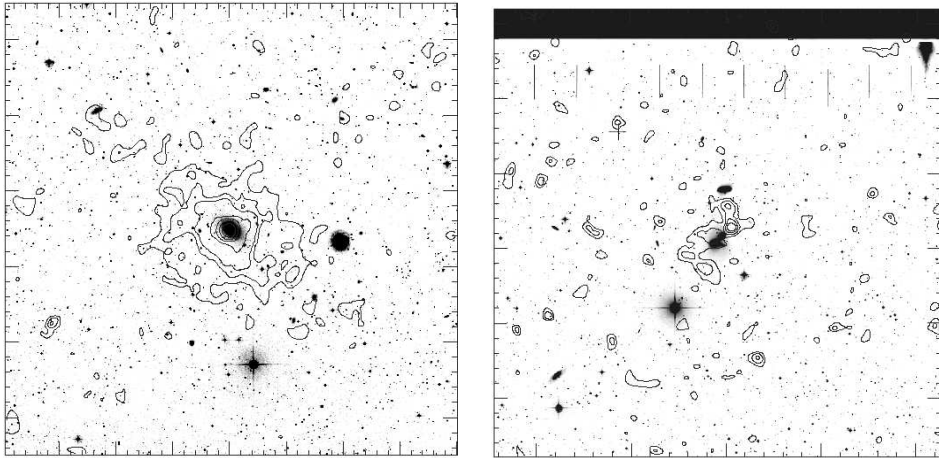


Figure 1. *Left:* A Digital Sky Survey image of the poor group NGC 533 (greyscale) with the ROSAT X-ray emission (contours) superimposed. Note the symmetric X-ray emission, the central, giant elliptical, and the dearth of late type galaxies. *Right:* A corresponding image of the poor group Hickson 90. In this group, the X-ray emission is not smooth, symmetric, or even apparently associated with the galaxies. Instead of one dominant central elliptical, there are several interacting galaxies, including late types, in the core.

X-ray emission, are not as easy to identify as real. The populations of dwarf galaxies present in the X-ray luminous groups are not observed in X-ray faint groups (Figure 2). Deeper spectroscopy is required to establish whether these poorer groups have fainter dwarfs, analogs to those galaxies in the Local Group fainter than the Small Magellanic Cloud.

## 2. Why Study Poor Groups?

Poor groups are important to studies of cosmology and galaxy evolution for reasons that include the ubiquity of the group environment, the fact that clusters of galaxies evolve hierarchically from the accretion of groups, and the likelihood of tidal interactions and mergers among group members. First, let us consider the prevalence of groups. More than half of the baryons in the nearby universe lie in groups (Fukugita *et al.* 1998), the intergroup medium may contribute to the population of high redshift absorption line systems (Mulchaey *et al.* 1996), and group environment plays a critical, if poorly-defined role, in the degree to which gravitational lens galaxies distort the light of background objects. In this last case, it is possible to estimate the fraction of lensing galaxies that lie in groups (Keeton, Christlein, & Zabludoff 2000). The best lenses are the most massive galaxies, which tend to be early types and to lie in the densest regions. However, the increase in the dwarf-to-giant galaxy ratio with environment density (§3) compensates for the morphology-density relation, causing the distribution of environments of lens and non-lens galaxies to be similar. We estimate that at least 25% of strong lensing galaxies are group or rich cluster members. As a consequence, the extended dark halo of groups and the individual halos of other

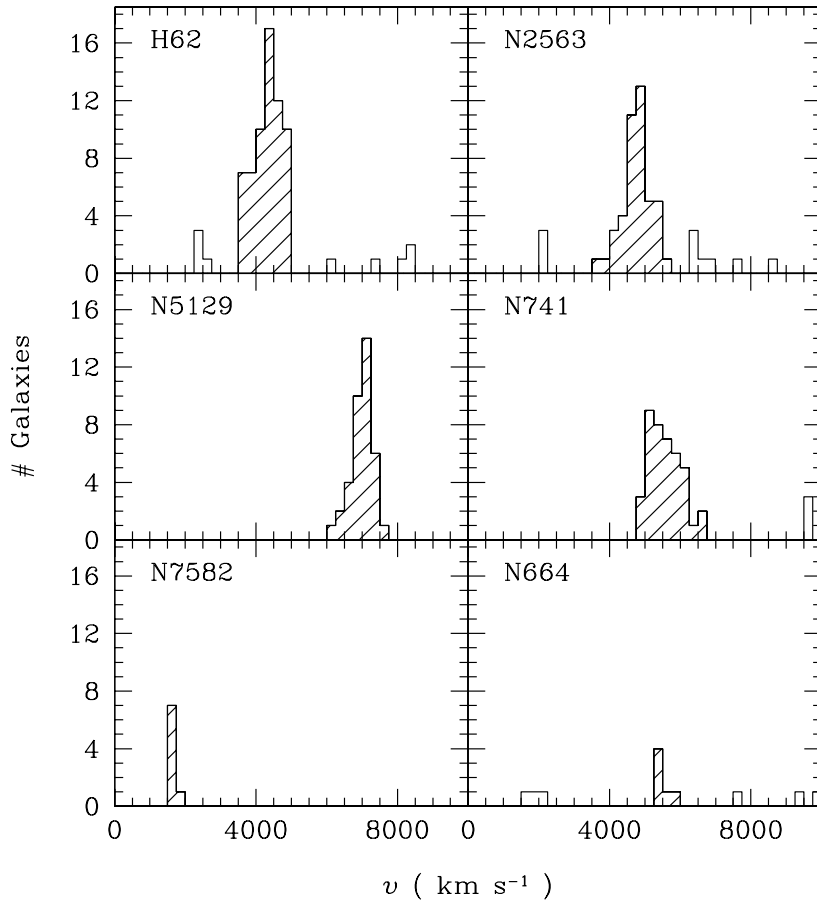


Figure 2. Galaxy velocity histograms for six poor groups. The first four have diffuse, luminous X-ray halos, the last two are not detected in X-rays. The non-detected groups also have fewer members, and thus we are unable to confirm that they are real, bound systems instead of chance superpositions of galaxies along the line-of-sight. We note, however, that the properties of the Local Group, which is bound (but not virialized), are consistent with those of the non-detected groups.

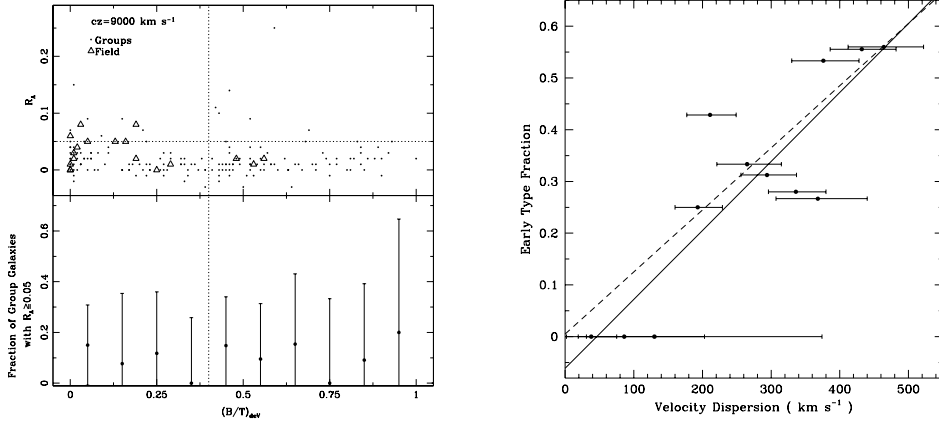


Figure 3. *Left:* Distribution of the asymmetry parameter  $R_A$  with respect to the fraction of galaxy light within the bulge component  $B/T$  (Tran *et al.* 2001). Galaxies with  $R_A > 0.05$  are considered significantly asymmetric. Galaxies with  $B/T > 0.4$  are classified bulge-dominated. *Right:* Early type fraction vs. velocity dispersion for poor groups in Zabludoff & Mulchaey 1998. The dashed and solid lines are weighted and unweighted fits, respectively.

group galaxies will significantly affect the lensing models and the constraints they place on halo shapes and cosmological parameters like  $H_0$  and  $\Lambda$ .

Second, the accretion of groups by rich clusters provides an opportunity to test the effects of cluster environment on galaxy evolution by comparing groups in the field to groups (subclusters) that have recently fallen into clusters. By comparing the galaxy morphologies and recent star formation histories for group galaxies in and out of clusters, it is possible to quantify the degree to which mechanisms such as ram pressure stripping or galaxy harassment — which are not as efficient in group environments — affect the evolution of cluster galaxies. Preliminary evidence suggests that the fraction and star formation histories of early types do *not* differ significantly from field groups to subclusters, suggesting that any external forces that drive galaxy evolution are not cluster-dependent but group-dependent (Zabludoff & Mulchaey 1998). One such mechanism is galaxy-galaxy tidal encounters and mergers, which are more efficient in poor groups than in clusters because the velocity dispersion of a group is similar to that of an individual galaxy.

Third, as likely sites for interaction-driven galaxy evolution, groups, especially the most dynamically young systems, are good places to look for galaxies evolving at  $z \sim 0$ . While evidence suggests that the cores of rich clusters have old, mostly unevolving galaxy populations, the beautiful HI map of the M81 group on the conference T-shirt (Yun *et al.* 1994) clearly shows that transforming interactions among galaxies can occur in poor groups today. Even though galaxy morphologies are frequently less revealing at optical wavelengths, optical imaging is abundant and worth examining for disturbed galaxies. In Tran *et al.* (2001), we obtain quantitative optical morphologies for galaxies in evolved, X-ray luminous groups by fitting the bulge and disk, subtracting the best model, and determining the asymmetric component of the residual light.

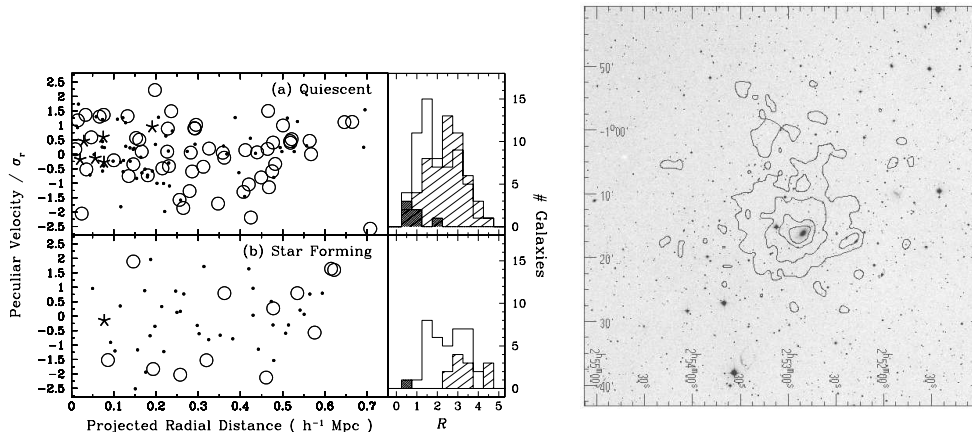


Figure 4. *Left:* Velocity offset vs. projected radial offset from the group centroid of (a) 123 quiescent and (b) 49 star-forming group members from six poor groups. The asterisks are the brightest group members ( $M_R \leq M_R^*$ ). The open circles are the giants defined by  $M_R^* < M_R \leq M_R - 19 + 5 \log h$ . The filled circles are the dwarfs ( $-19 + 5 \log h < M_R \leq -17 + 5 \log h$ ). Also plotted is the distribution of  $R$ , the quadrature sum of the x- and y-axis offsets of each galaxy, for the brightest (heavily shaded), giant (shaded), and dwarf populations (unshaded). The different  $R$  distributions suggest that the three populations occupy distinct orbits. *Right:* A Digital Sky Survey image of the isolated elliptical NGC 1132 (greyscale) with the ASCA X-ray emission (contours) superimposed (Mulchaey & Zabludoff 1999).

Figure 3 shows that  $\sim 15\%$  of these galaxies, including both early and late types, are significantly asymmetric. The presence of obvious tidal features in some of these galaxies suggests that morphologically-disruptive interactions can take place even in dynamically older groups.

While such interactions may be more common in lower velocity dispersion, less evolved groups like the Local Group and the M81 system, there is indirect evidence that interactions have played a role in most groups at some time. For example, Figure 3 shows a strong correlation between the early type fraction and velocity dispersion of poor groups. Either both quantities increase as groups evolve or the initial size of the group potential determines the early type fraction for all time. Some support for the former scenario comes from the saturation point in early type fraction beyond which the morphological compositions of groups and clusters are similar. This saturation point is about  $500 \text{ km s}^{-1}$ , the velocity dispersion that a group must have such that an  $L^*$  galaxy would have merged with another member within a Hubble time.

### 3. The Group Galaxy Luminosity Function

If interactions can alter the morphology of group galaxies, they can also affect galaxy luminosity. We might expect the ratio of dwarf-to-giant galaxies ( $D/G$ ) to be dependent on both the initial luminosity distribution when most galaxies formed and the subsequent evolution of galaxy luminosity and number density.

In both cases, the environment may play a role. For example, standard biased galaxy formation models (White *et al.* 1987) predict that giant galaxies are more likely than dwarfs to form in dense regions. Subsequent evolution via galaxy-galaxy mergers, tidal interactions, ram pressure stripping, or other factors would alter  $D/G$  in a direction and to a degree that are dependent on the dominant mechanism. To test the dependence of  $D/G$  on environment, we investigate whether  $D/G$  varies among poor groups with different galaxy number densities, *within* groups with radius, and from the field to groups to rich clusters.

We find that the galaxy luminosity function is not universal — the group with the faintest X-ray emission and lowest galaxy number density has a significantly lower  $D/G$  than the other six systems in our sample. Furthermore, the average  $D/G$  for the five X-ray luminous groups is larger than that derived from the Las Campanas Redshift Survey field (Lin *et al.* 1996) and consistent with that of rich clusters (cf. Trentham 1997)<sup>1</sup>. Within the composite group,  $D/G$  drops significantly with increasing radius (and thus decreasing density). These three trends are in the same sense and suggest that, at least in some environments, dwarfs are more biased than giants with respect to dark matter. Thus more than just standard biased galaxy formation is at work (Zabludoff & Mulchaey 2000).

Evidence that the group dwarf and giant populations formed at different times is presented in Figure 4. The phase-space diagram shows that the dwarfs and giants have not mixed, *i.e.*, lie on different orbits. Possible explanations for this result and the trends in  $D/G$  summarized above include inefficient galaxy formation (*e.g.*, giants form less efficiently in denser environments), increases in the satellite-to-primary ratio through the mergers of giant galaxies, and dwarf formation in the tidal tails of giant merger remnants (Barnes & Hernquist 1992).

Additional support that  $D/G$  evolves comes from X-ray and optical observations of the isolated elliptical NGC 1132 (Figure 4). Numerical simulations predict that some poor groups of galaxies have merged by the present epoch into giant ellipticals (Barnes 1989). The extent ( $\sim 250$  kpc  $h^{-1}$ ), temperature ( $\sim 1$  keV), metallicity ( $\sim 0.25$  solar), and luminosity ( $\sim 2.5 \times 10^{42}$   $h^{-2}$  ergs  $s^{-1}$ ) of NGC 1132’s X-ray halo are comparable with those of poor group halos. The total mass inferred from the X-ray emission,  $\sim 1.9 \times 10^{13}$   $h^{-1}$   $M_{\odot}$ , is also like that of an X-ray detected group. Optical imaging uncovers a dwarf galaxy population clustered about NGC 1132 that is consistent in number density and projected radial distribution with that of an X-ray group. The similarities of NGC 1132 to poor groups in both the X-ray band and at the faint end of the galaxy luminosity function, combined with the deficit of luminous galaxies in the NGC 1132 field, are compatible with the merged group picture. Another possibility is that the NGC 1132 system is a “failed” group (*i.e.*, a local overdensity in which other bright galaxies never formed).

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<sup>1</sup>The similarity of  $D/G$  for groups and clusters once groups reach a large enough gravitational well depth is reminiscent of the saturation of the early type fraction-velocity dispersion relation noted in the previous section.

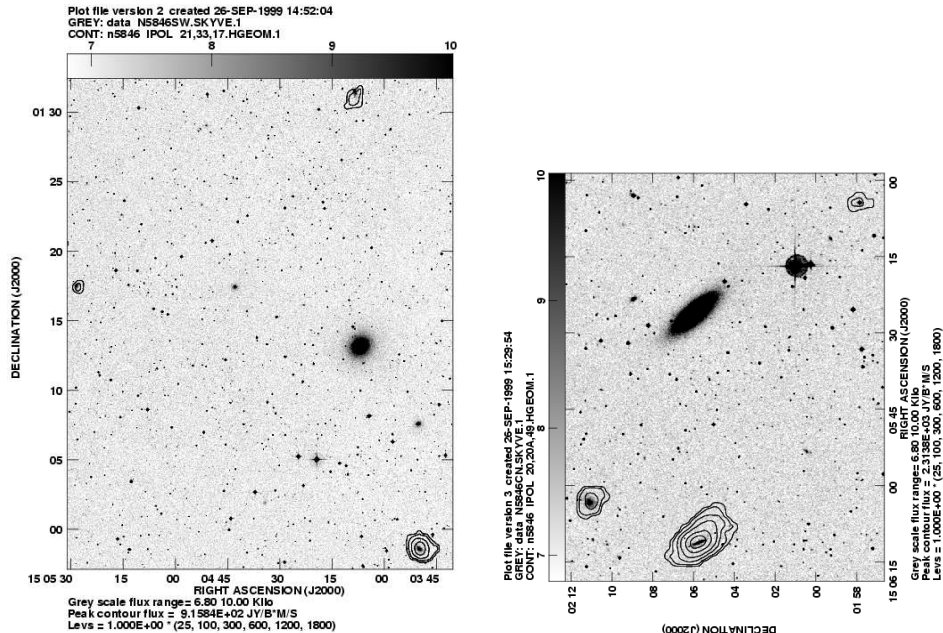


Figure 5. Two images from our VLA mosaic survey of the NGC 5846 poor group showing several HI detections (contours) of group members.

#### 4. Cold Gas in Groups

In the previous sections, we discussed the galaxies and hot gas in poor groups, but what about the cold gas? HI studies of groups can tell us both about interactions among galaxies — witness the M81 group — and about galaxy formation efficiency in groups. Our on-going HI survey with the VLA (Zabludoff with van Gorkom, Wilcots, & Mulchaey) targets not just group members, but the entire  $1.5 \times 1.5$  square degree field of each group with 36 pointed mosaic tiles. Of the two groups examined so far, we have made  $\sim 15$  HI detections of galaxies with a range of optical types and luminosities (Figure 5).

Our preliminary results include an increase in the HI extent of galaxies with projected radius from the group center. However, this trend might be due to the increasing spiral fraction with projected radius — we are currently comparing the magnitudes of these two effects. Most of our detections are near the  $\sim 10^7 M_\odot$  limit of the survey, so many other detections may be possible at fainter limits. We observe no obvious galaxy-galaxy interactions like those in M81, but fewer HI-rich interactions are expected in these more dynamically evolved, X-ray detected, high early type fraction groups. All HI clouds lie at the positions of galaxies, *i.e.*, there are no “free” clouds down to our detection limit that could be associated with evolution of group as whole (cf. Blitz *et al.* 1999) instead of individual galaxies.

## 5. Conclusions

Groups are where a lot of the action is (or was) in galaxy evolution. There are optical and HI signatures of on-going galaxy-galaxy interactions, not only in M81, but also to a lesser degree in more dynamically evolved, X-ray luminous groups. There is also indirect evidence that groups, and the mergers and tidal encounters likely to occur in such low velocity dispersion systems, played an important role in the past evolution of galaxies. The galaxy populations of X-ray luminous poor groups and rich clusters, including the early type fraction, fraction of early types forming stars, and dwarf-to-giant ratio, are surprisingly similar. These results suggest that group-dependent, not cluster-dependent, mechanisms like galaxy-galaxy interactions drive the evolution of those galaxies that begin as members of groups accreted by clusters<sup>2</sup>.

Additional evidence for environment-dependent evolution is the increase in the dwarf-to-giant ratio with density, at least up to the densities of X-ray luminous groups and clusters, indicating that more than standard biased galaxy formation is at work. The dwarf and giant galaxies in groups have not mixed, suggesting that one population formed later. This evolution in  $D/G$  might be due to galaxy-galaxy interactions; a compelling example is NGC 1132, an isolated giant elliptical with all the hallmarks of a merged group. On-going HI studies with the VLA have the potential to place critical constraints on the interaction history and galaxy formation efficiency in such groups.

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<sup>2</sup>Even the  $\sim 400 \text{ km s}^{-1}$  upper limit on the velocity dispersion of a giant elliptical galaxy is consistent with the velocity dispersion of a group — is this limit due to the initial formation of such galaxies in group, not cluster, environments? Further support for this idea comes from the tendency of the brightest giant ellipticals to lie in the spatial and kinematic centers of groups and subclusters, not clusters (Beers & Geller 1983; Zabludoff & Mulchaey 1998).