COMPACT GROUPS OF GALAXIES

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ABSTRACT

Compact groups of galaxies have posed a number of challenging questions. Intensive observational and theoretical studies are now providing answers to many of these, and at the same time, are revealing unexpected new clues about the nature and role of these systems. Most compact groups contain a high fraction of galaxies having morphological or kinematical peculiarities, nuclear radio and infrared emission, and starburst or active galactic nuclei (AGN) activity. They contain large quantities of diffuse gas and are dynamically dominated by dark matter. They most likely form as subsystems within looser associations and evolve by gravitational processes. Strong galaxy interactions result and merging is expected to lead to the ultimate demise of the group. Compact groups are surprisingly numerous, and may play a significant role in galaxy evolution.

1. INTRODUCTION

As their name suggests, compact groups are small systems of several galaxies in a compact configuration on the sky. The first example was found over one hundred years ago by Stephan (1877) who observed it visually using the 40-cm refractor of the Observatoire de Marseille. Stephan's Quintet is a small group of five galaxies, three of which show strong tidal distortions due to gravitational interaction. A second example was found 71 years later by Seyfert (1948) from a study of Harvard Schmidt plates. Seyfert's Sextet (Figure 1) is one of the densest groups known, having a median projected galaxy separation of only $6.8h^{-1}$ kpc (the Hubble Constant $H_0 = 100h$ km s^{-1} Mpc^{-1}).

The Palomar Observatory Sky Survey (POSS) provided a new and extensive resource for the systematic investigation of small groups of galaxies. Two catalogs, the *Atlas of*

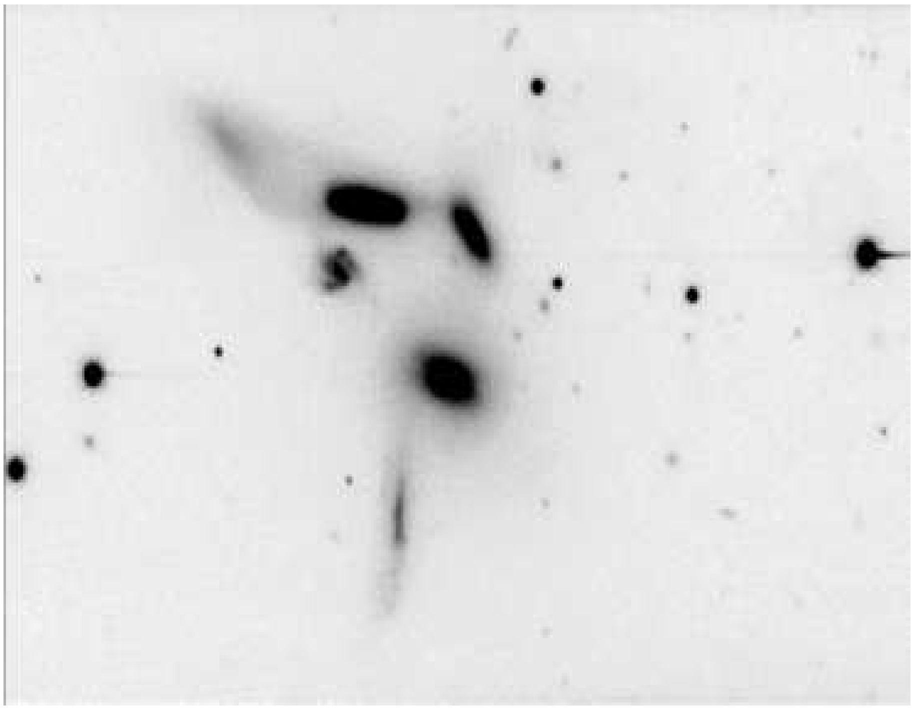

Fig. 1.— Seyfert's Sextet. Discovered in 1948, this group of five galaxies is one of the densest known. The sixth object appears to be a tidal plume. The small face-on spiral galaxy has a redshift that is more than four times larger than those of the other galaxies.

Interacting Galaxies (Vorontsov-Velyaminov 1959, 1975) and the *Atlas of Peculiar Galaxies* (Arp 1966), contain galaxies or galaxy groups selected on the basis of visible signs of interaction or peculiar appearance. In addition to Stephan's quintet and Seyfert's Sextet, these include many new compact groups, including a striking chain of five galaxies, VV 172. Prior to these, Shakhbazian (1957) had discovered a small dense cluster of 12 faint red galaxies that appeared so compact that they were initially mistaken for stars. Over the next two decades, Shakhbazian and collaborators examined over 200 POSS prints covering 18% of the sky and cataloged 376 additional "compact groups of compact galaxies" (Shakhbazian 1973, Shakhbazian & Petrosian 1974, Baier et al 1974, Petrosian 1974, 1978, Baier & Tiersch 1975-79). Apart from occasional photographic or spectroscopic observations (eg. Mirzoian et al 1975, Tiersch 1976, Massey 1977, Shakhbazian & Amirkhanian 1979, Vorontsov-Velyaminov et al 1980, Vorontsov-Velyaminov & Metlov 1980) these systems initially received little attention. However, interest in them is growing. Although the majority seem to be small clusters, they share some of the properties, and pose some of the same questions, as do compact groups.

When redshifts were measured for galaxies in the first compact groups (Burbidge & Burbidge 1959, 1961a), surprises were found. Both Stephan's Quintet and Seyfert's Sextet contain a galaxy with a discordant redshift. It seemed unlikely that a foreground or background galaxy would appear so often projected within such compact systems (Burbidge & Burbidge 1961a). This impression was further reinforced with the discovery of yet another discordant redshift in VV 172 (Sargent 1968). Are these examples of physical association between objects of widely different redshifts, as has been advocated for many years by Arp (1987)?

Even if the discordant galaxies are ignored, the velocity dispersions of these systems are generally higher than would be expected given their visible mass (Burbidge & Burbidge 1959, 1961b, 1961c, Burbidge & Sargent 1971). It was argued that such groups must be unbound and disrupting (eg. Ambartsumian 1961), although Limber and Mathews (1960) showed that the virial theorem could be satisfied for Stephan's Quintet, given the uncertainties in the projection factors, if the individual galaxy masses were considerably larger than those of isolated galaxies. The observations can of course also be explained if the bulk of the mass is in a non-visible form. In hindsight, this was one of the earliest indications of the possible existence of dark matter in galactic systems.

A new problem emerged with the realization that bound groups would be unstable to orbital decay resulting from gravitational relaxation processes (Peebles 1971). A simple calculation indicated that the dynamical-friction timescale was much shorter than the Hubble time (Hickson et al 1977), as was soon confirmed by numerical simulations

(Carnevali et al 1981). At the same time, it became increasingly clear that mergers played an important role in the evolution of many, if not all, galaxies (Press & Schechter 1974, Ostriker & Tremaine 1975). Compact groups emerged as prime locations for investigations of the dynamical evolution of galaxies.

Motivated by the desire for a homogeneous sample that could be subject to statistical analysis, Rose (1977), and later, Hickson (1982) produced the first catalogs of compact groups having specific, quantitative, selection criteria. Subsequent detailed investigation, at many wavelengths, has produced a large body of observational data for the Hickson catalog. As a result, it has now become possible to address some of the outstanding questions concerning the nature of compact groups and their role in galaxy evolution. Not surprisingly, new questions have been raised and new controversies have appeared. However, much progress has been made in resolving both old and new issues.

This review is organized as follows: In Section 2, the definition of a compact group is discussed, along with methods of identification and surveys that have been made. In Sections 3-5, observed properties of these systems are summarized and discussed. Sections 6 and 7 focus mainly on interpretation of the observations, and on implications of these results. All work on compact groups of galaxies cannot possibly be discussed in this short paper, although an attempt is made to touch upon most current topics. Other recent reviews of compact groups and closely related subjects include those by White (1990), Hickson (1990, 1997), Whitmore (1992), Kiseleva & Orlov (1993), Sulentic (1993), and Mamon (1995).

2. IDENTIFICATION AND SURVEYS

By "compact group", we mean a small, relatively isolated, system of typically four or five galaxies in close proximity to one another. Such groups do not necessarily form a distinct class, but may instead be extreme examples of systems having a range of galaxy density and population. Because of this, the properties of the groups in any particular sample may be strongly influenced by the criteria used to define the sample. The early surveys used qualitative criteria that, while successful in finding many interesting individual objects, do not easily allow one to draw broad conclusions about the groups as a whole. Thus, the focus in recent years has been on samples selected using specific, quantitative, criteria. These criteria define the minimum number and magnitude range of the galaxies, and also consider the galaxy spatial distribution.

The use of quantitative selection criteria was pioneered by Rose (1977) who searched for groups that have three or more galaxies that are brighter than a limiting magnitude of 17.5, and that have a projected surface density enhancement of a factor of 1000 compared to the surrounding background galaxy density. Searching an area of 7.5% of the sky, he found 170 triplets, 33 quartets, and 2 quintets. Unfortunately, the sample received little follow-up study. Sulentic (1983) re-examined the 35 Rose groups which contain four or more galaxies and found that only a third actually satisfied the selection criteria. This is testimony to the difficulty of visual searches. A more fundamental problem is that the fixed magnitude limit in the selection criteria makes the sample susceptible to strong distance-dependent biases.

In an attempt to reduce such effects, Hickson (1982, 1993, 1994) adopted a relative magnitude criterion, selecting systems of four or more galaxies whose magnitudes differ by less than 3.0. A distance independent (to first order) compactness criterion was employed: $\bar{\mu}_G < 26$, where $\bar{\mu}_G$ is the mean surface brightness of the group calculated by distributing the flux of the member galaxies over the smallest circular area containing their geometric centers. To avoid including the cores of rich clusters, an isolation criterion was necessary so as to reject the group if a non-member galaxy, not more than 3 mag fainter than the brightest member, occurred within three radii of the center of the circle. (A non-member galaxy is a galaxy which if included in the group would cause the group to fail one or more of the selection criteria.) From a search of 67% of the sky (all the POSS prints), and using magnitudes estimated from the POSS red prints, exactly 100 groups were found satisfying these criteria (hereafter HCG's). As the HCG sample is now the most widely studied, it is important to examine the biases introduced by the criteria, and by the visual search procedure.

Any sample selected on the basis of surface density will suffer from geometric and kinematic biases. The former occurs because non-spherical systems will be preferentially selected if they are oriented to present a smaller cross-sectional area (eg. prolate systems pointed towards us); the latter because we will preferentially select systems that, owing to galaxy orbital motion, are momentarily in a more compact state (transient compact configurations). Thus, a compact group might result from a chance alignment or transient configuration within a loose group (Mamon 1986). This question will be considered in more detail in Section 6.2.

Other biases arise from the subjective nature of the search procedure. The original catalog contains a few mis-identifications, such as compact galaxies mistaken for stars, and marginal violations of the isolation criteria. In addition, when photometry was obtained for the galaxies in the catalog (Hickson et al 1989), it was found that some groups would not satisfy the selection criteria if photometric magnitudes are used. Attempts to rectify these problems have been made by Hickson et al (1989) and Sulentic (1997). However, it should be emphasized that changes, such as using photometric magnitudes in the selection criteria, are not corrections to the catalog, but are actually the imposition of *additional* a postiori selection criteria. The resulting subsample is by no means complete because the new criteria are applied only to the visually-selected HCG catalog and not to the entire sky.

Because of the difficulty of identifying faint groups, the HCG catalog starts to become significantly incomplete at an integrated magnitude of about 13 (Hickson et al 1989, Sulentic & Rabaça 1994). A more subtle effect results from the difficulty of recognizing low-surface-brightness groups. Because of this, the catalog also becomes incomplete at surface brightnesses fainter than 24 (Hickson 1982). Yet another effect is that groups may be more noticeable if the magnitude spread of their members is small. Thus, the catalog may also be incomplete for magnitude intervals greater than about 1.5 (Prandoni et al 1994). These effects are of critical importance in statistical analyses of the sample. One immediate conclusion is that the actual number of groups which satisfy the selection criteria may be considerably larger than the number found by a subjective search.

It has recently become feasible to find compact groups by automated techniques. Mamon (1989) used a computer to search Tully's (1987) catalog of nearby galaxies and identified one new compact group, satisfying Hickson's criteria, in the Virgo Cluster. Prandoni et al (1994) applied similar criteria to digital scans of ~ 1300 deg^2 around the southern galactic pole and detected 59 new southern compact groups (SCGs). Observations are presently underway to obtain accurate photometry and redshifts for this sample (Iovino private communication). The digitized Palomar Sky Survey II also offers new opportunities for the identification of compact groups (De Carvalho & Djorgovski 1995).

An alternative approach is to identify groups of galaxies from redshift information, as was first done by Humason et al (1956). With the advent of large-scale redshift surveys, it has become possible to identify a reasonably-large sample of compact groups in this way. Barton et al (1996) have compiled a catalog of 89 redshift-selected compact groups (RSCGs) found by means of a friends-of-friends algorithm applied to a complete magnitude-limited redshift survey. Galaxies having projected separations of $50h^{-1}$ kpc or less and line-of-sight velocity differences of 1000 km s^{-1} or less are connected and the sets of connected galaxies constitute the groups. The numerical values were chosen to best match the characteristics of the HCG sample, and indeed, many of those RSCGs that have at least four members are also HCGs. There are some significant differences, however: Because foreground and background galaxies are automatically eliminated by the velocity selection criteria, this technique is more effective at finding groups in regions of higher galaxy density, which would fail the HCG isolation criterion. This criterion requires that the distance to the nearest neighbor be at least as large as the diameter of the group. The RSCG criteria, on the other hand, require only that the nearest-neighbor distance be larger than the threshold distance ($50h^{-1}$ kpc for the RSCGs), which may be considerably smaller. It will therefore allow the inclusion of groups that are physically less isolated (and therefore less physically distinct) than would the HCG criterion. One would also expect that the numbers of groups found in a given volume by the less-restrictive RSCG criteria to be larger than by the HCG criteria, as seems to be the case. While the redshift-selection method compliments the HCG angular-selection technique, one should keep in mind that it also selects groups according to apparent (projected) density – the velocity information serves only to reject interlopers. Thus it will be subject to some of the biases discussed above. Also, because the galaxy sample used is magnitude-limited, rather than volume-limited, there will be redshift-dependent biases in the RSCGs. However, the well-defined selection criteria and the completeness of the sample, should allow a quantitative determination of the effects of this bias.

3. SPACE DISTRIBUTION AND ENVIRONMENT

The space distribution and environment of compact groups provides important clues to their nature. The median redshift of the HCGs is $z = 0.030$, placing most of them at distances well beyond the Virgo Cluster (Hickson et al 1992). A cursory inspection reveals that they are fairly uniformly distributed and show no preference for rich clusters. This is at least partly due to the isolation criterion. However, galaxies in rich clusters have rather different kinematical and morphological properties than do those in compact groups, so one might justifiably argue that small clumps of galaxies within clusters are not compact groups.

A natural question is whether or not compact groups are associated with loose groups. Rood & Struble (1994) observed that 70% of the HCGs are located within the bounds of cataloged loose groups and clusters. Studies of the distribution of galaxies in redshift space (Vennik et al 1993, Ramella et al 1994, Sakai et al 1994, Garcia 1995, Barton et al 1996) indicate that compact sub-condensations do occur within loose groups and filaments. Vennik et al (1993) and Ramella et al (1994) find that most HCGs are indeed associated with loose groups.

While the above studies show that compact groups trace large-scale structure, it is also clear that they prefer low-density environments. Sulentic (1987), Rood & Williams (1989), Kindl (1990), and Palumbo et al (1995) have examined the surface density of galaxies surrounding the groups. They generally agree that about two-thirds groups show no statistically significant excess of nearby neighbors. This is not inconsistent with the redshift-space results because most of the HCG associations identified by Ramella et al (1996) contain fewer than 5 excess galaxies. Thus while compact groups are associated with loose groups and filaments, these tend to be low-density and sparsely-populated systems.

Are the galaxies in compact groups in any way distinct from those in their immediate environments? Rood & Williams (1989) and Kindl (1990) both found that compact groups, including those in rich environments, contain a significantly smaller fraction of late-type (spiral and irregular) galaxies than do their neighborhoods. This result is of particular importance to the question of the physical nature of compact groups, discussed below in Section 6. In addition, many independent studies have found significant differences between galaxies in compact groups and those in other environments. These are examined in Section 5.

4. DYNAMICAL PROPERTIES

The first studies of individual compact groups (Burbidge & Burbidge 1959, 1961b, 1961c, Burbidge & Sargent 1971, Rose & Graham 1979, Kirshner & Malumuth 1980) indicated short dynamical times and mass-to-light ratios intermediate between those of galaxies and rich clusters. However, because of the small number of galaxies, estimates of the space velocities and physical separations of galaxies in individual groups are highly uncertain. Meaningful dynamical conclusions about systems containing only four or five galaxies requires statistical analysis of large homogeneous samples.

By 1992, velocities had been measured for almost all 462 galaxies in the HCG catalog (Hickson et al 1992). The distribution of galaxy velocities, relative to the median of each group, is shown in Figure 2. It can be seen that the majority of velocities fall within a roughly Gaussian distribution of standard deviation $\sim$ 250 km s^{-1} (the sharp peak at zero velocity results from the use of the median). This characteristic velocity is quite similar to velocity dispersions found in loose groups, and much smaller than typical velocity dispersions in rich clusters. In addition to the Gaussian core, a flat component is seen in the velocity distribution of Figure 2. This is expected as some galaxies which are not physically related to the group will appear projected on the group by chance. This component contains about 25% of the total number of galaxies. Whether of not chance projection can account for such a large number of "discordant" galaxies is still a matter of some debate, and is discussed further in Section 6.1.

For a system of characteristic linear size R and internal velocity V, a characteristic dynamical time is $t_d = R/V$. A characteristic mass density is $\rho = 1/Gt_d^2$, from which one

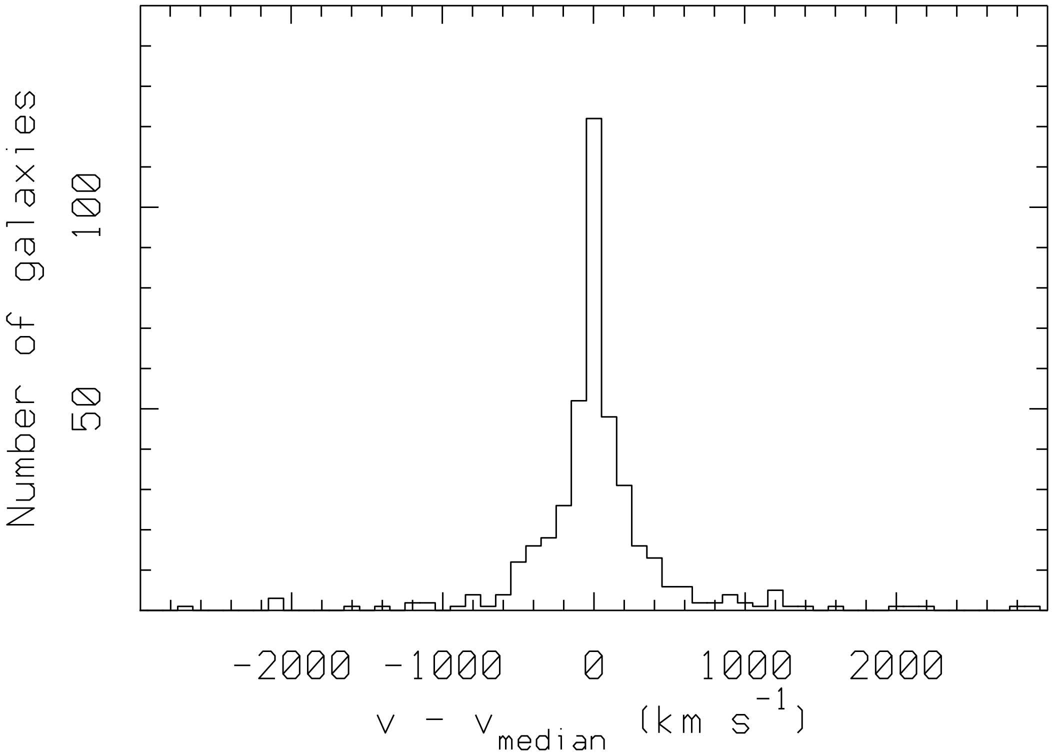

Fig. 2.— Velocity distribution of galaxies in compact groups. The figure shows the distribution of the difference between the observed galaxy radial velocity and the median velocity of galaxies in the group to which it belongs, for 410 galaxies in the HCG catalog. Most galaxies (77%) have velocity differences less than 500 km s^{-1} from the median.

can estimate the total mass within the region occupied by the galaxies. After removing galaxies whose velocities differ from the group median by more that 1000 km s^{-1}, Hickson et al (1992) found that $t_d \sim 0.02 H_0^{-1}$ and obtained a mean mass-to-light ratio of $50h$ (solar units) for the HCGs. Similar values were found for several Shakhbazian groups (Tikhonov 1986, Amirkhanian & Egikian 1987, Amirkhanian 1989, Lynds et al 1990, Amirkhanian et al 1991). Since the mass-to-light ratios of individual HCG galaxies is on the order of $7h$ (Rubin et al 1991), the galaxies appear to contain only $\sim 15\%$ of the total mass.

5. STRUCTURE AND MORPHOLOGY

The spatial distribution and luminosities of the member galaxies provides further clues to the nature of compact groups. If they are primarily projections or transient configurations, the luminosity function should be the same as that of the parent systems, and the spatial distribution of the galaxies should be consistent with a random distribution. If they are bound physical systems, the luminosity function and spatial distribution might show features that reflect the origin or subsequent evolution of compact groups.

5.1. Shapes and orientations

The shapes of compact groups were first investigated by Arp (1973) who concluded that galaxy "chains" were unusually predominant. However, Rose (1977) determined that the ellipticities of his groups were consistent with a random distribution of galaxies. Using the larger HCG sample, Hickson et al (1984) and Malykh & Orlov (1986) reached the same conclusion as Arp – the groups are typically more elongated than would be a random distribution of galaxies. An immediate consequence of this result is that compact groups cannot easily be explained as random projections or chance crossings, as this would largely erase any inherent ellipticity of a parent loose group. From static simulations, Hickson et al (1984) concluded that the observed ellipticities are best matched by three-dimensional shapes that are intrinsically prolate. The same result was found by Oleak et al (1995) in a recent study of the shapes of 95 Shakhbazian compact groups. These conclusions, however, are not unique. Hickson et al (1984) also found the shapes to be consistent with those seen in dynamical simulations of compact groups seen in projection as subgroups within loose groups. In addition, one must always be concerned about possible selection biases. It may be that highly elongated groups (such as VV 172) are more easily noticed in visual searches. It will be interesting to see if these results are confirmed by studies of groups found by automated searches.

If the intrinsic shapes of compact groups are related to their formation process, one might expect to see a relationship between the orientation angle of a group and the environment. Palumbo et al (1993) examined the environments of the HCGs, and found that the orientations of the major axes of the groups were consistent with an isotropic distribution.

If compact groups are not simply projection effects, they might be expected to show a centrally-concentrated surface density profile, as is seen in clusters of galaxies. Although the number of galaxies in individual compact groups is small, with a large sample it is possible to estimate a mean profile. By scaling and superimposing the HCGs, Hickson et al (1984) found evidence for central concentration. Mendes de Oliveira & Girard (1994), using a similar analysis, concluded that the mean surface density profile is consistent with a King (1962) model with typical core radius of $15h^{-1}$ kpc. Most recently, Montoya et al (1996) have analyzed the profiles of the 42 HCG quartets which have accordant redshifts. Their technique uses the distribution of projected pair separations and thus avoids assumptions about the location of the group center. They find a smaller core radius ($6h^{-1}$ kpc for a King model). The fact that Montoya et al (1996) find a consistent density profile for all groups, without any scaling, is particularly interesting. This would not be expected if most groups are chance alignments within loose groups. It also implies that compact groups have a unique scale, which seems counter to the concept of hierarchical clustering. Montoya et al (1996) suggest that this arises as a result of a minimum mass density and velocity dispersion that is required for the groups to be virialized (Mamon 1994).

5.2. Compact-group galaxies

There have been several studies of the morphological types of galaxies in compact groups (Hickson 1982, Williams & Rood 1987, Sulentic 1987, Hickson et al 1988b). Most studies agree that the fraction f_s of late type galaxies is significantly less in compact groups than in the field. Hickson et al (1988b) find $f_s = 0.49$ for the HCGs; Prandoni et al (1994) obtain $f_s = 0.59$ for the SCGs. Both these values are substantially lower than those found for field galaxy samples ($f_s \simeq 0.82$, Gisler 1980, Nilson 1973).

Also well established is morphological type concordance, observed in both the HCGs and SCGs (Sulentic 1987, Hickson at al 1988b, Prandoni et al 1994). A given compact group is more likely to contain galaxies of a similar type (early or late) than would be expected for a random distribution. White (1990) has pointed out that such concordance could result from a correlation of morphological type with some other property of the group. The strongest such correlation found to date is between morphological type and velocity dispersion (Hickson et al 1988b). As Figure 3 shows, groups with higher velocity dispersions contain fewer late-type (gas-rich) galaxies. They also tend to be more luminous. The importance of velocity dispersion, in addition to local density, on the galaxy morphology had previously been emphasized by De Souza et al (1982). A crucial clue is that the morphology-density relation seen in clusters and loose groups (Dressler 1980, Postman & Geller 1984, Whitmore & Gilmore 1992) is not the dominant correlation in compact groups (Hickson et al 1988b), although some effect is present (Mamon 1986). This suggests that the velocity dispersion is more fundamental, ie of greater physical relevance to the formation and evolution of galaxies in compact groups, than is apparent physical density.

There is much evidence that interaction is occurring in a large fraction of galaxies in compact groups. The strongest direct support comes from kinematical studies. Rubin et al (1991) found that two thirds of the 32 HCG spiral galaxies that they observed have peculiar rotation curves. These show asymmetry, irregularity and in some cases extreme distortion, characteristic of strong gravitational interaction. This result has recently been challenged by Mendes de Oliveira et al (preprint) who obtained H_α velocity maps for 26 HCG spiral galaxies and found that only 1/3 showed abnormal rotation curves. They suggest that the difference is due to the more-complete spatial sampling of their data.

In their study, Rubin et al (1991) observed 12 HCG elliptical galaxies and detected nuclear emission in 11 of them. This high fraction suggests that interactions and mergers may be supplying gas to these galaxies. This idea received independent support from radio observations in which neutral hydrogen emission was detected in three compact groups which contain only elliptical galaxies (Huchtmeier 1994).

Zepf & Whitmore (1993) found that elliptical galaxies in compact groups tend to have lower internal velocity dispersions than do ellipticals in other environments having the same effective radii, absolute magnitudes and colors. They therefore do not lie on the fundamental plane defined by other elliptical galaxies. This discrepancy correlates with isophote shape in that those galaxies that have “disky” or irregular isophotes tend to have lower velocity dispersion. Both Zepf & Whitmore (1993) and Bettoni & Fasano (1993, 1995, 1996, Fasano & Bettoni 1994) report that HCG elliptical galaxies are less likely to have “boxy” isophotes, and more likely to have irregular isophotes. Such effects are consistent with results of simulations of tidal encounters (Balcells & Quinn 1990).

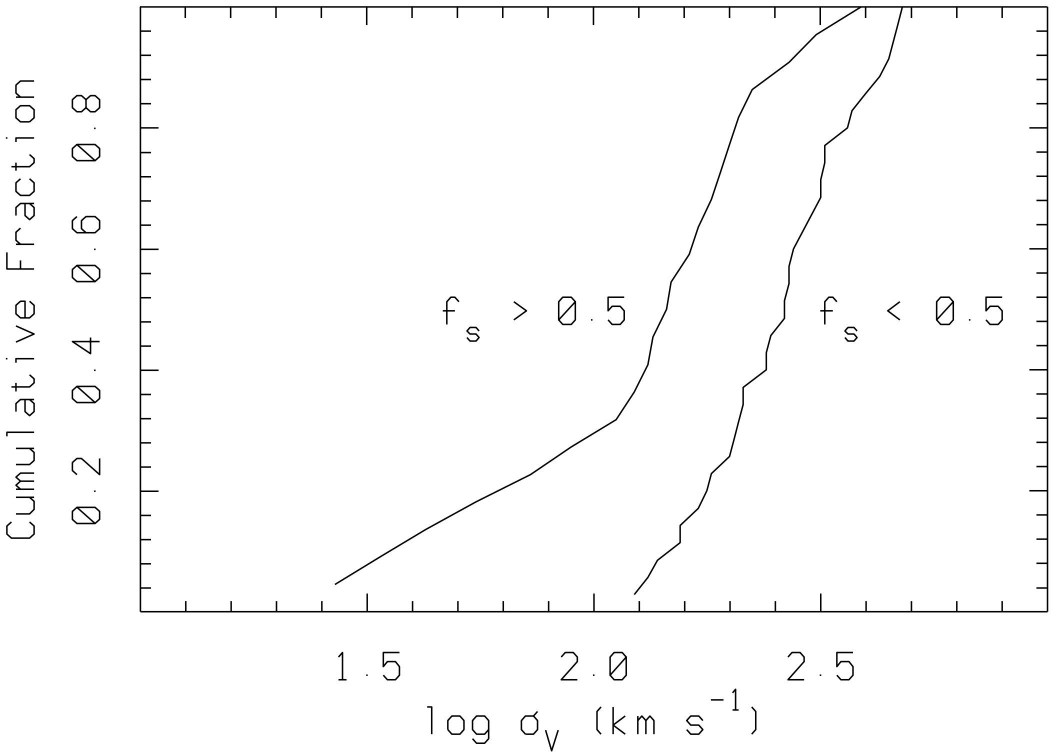

Fig. 3.— Morphology-velocity correlation for compact groups. The figure shows the cumulative distributions of velocity dispersion for spiral rich ($f_s > 0.5$) and spiral-poor ($f_s < 0.5$) groups. The former have typically half the velocity dispersion than the latter and a broader velocity range.

5.3. Optical luminosity function

The luminosity function of compact groups was first estimated by Heiligman & Turner (1980). They examined a sample consisting of Stephan's Quintet, Seyfert's Sextet and eight more compact groups from the Arp and Vorontsov-Velyaminov catalogs, and concluded that compact groups contain relatively fewer faint galaxies than does a comparable field galaxy sample. Analysis of the relative luminosities within individual HCGs (Hickson 1982), and studies of several Shakhbazian groups (Kodaira et al 1991), showed a similar effect, although Tikhonov (1987) found a luminosity function similar to that of field and cluster galaxies.

The larger HCG sample allows the question of the galaxy content of compact groups to be addressed with greater certainty. The standard technique for determination of the luminosity function weights each galaxy by V_m/V, where V is the volume of the smallest geocentric sphere containing the group, and V_m is the volume of the largest such sphere within which the group could have been detected. Using this approach Sulentic and Rabaça (1994) obtained a luminosity function for HCG galaxies similar to that of field galaxies. However, Mendes de Oliveira and Hickson (1991) argued that the standard calculation does not address the selection effects of the HCG sample. For example, the luminosity range within an individual group is limited by the 3-mag range of the selection criteria. Because of this, fainter galaxies within compact groups are not included in the catalog. In order to account for such biases they used a modeling technique in which galaxies were drawn from a trial luminosity function and assigned to groups. Redshifts were given to each group according to the observed distribution, and groups that failed to meet the HCG selection criteria were rejected. The luminosity distribution of the resulting galaxy sample was then compared to the observations and the process repeated with different trial luminosity functions. Their best-fit luminosity function is deficient in faint galaxies, although a normal field-galaxy luminosity function is not excluded.

To avoid the selection problem, Ribeiro et al (1994) obtained deeper photometry for a subsample of the HCGs in order to include the fainter galaxies explicitly. Since redshifts are not known for these galaxies, a correction for background contamination was made statistically. The luminosity function that they obtained is similar to that of field galaxies. Most recently, the luminosity function for the RSCGs has been computed by Barton et al (1996). They find it to be mildly inconsistent with that of field-galaxies, in the same sense as that of Mendes de Oliveira & Hickson (1991) for the HCGs. Figure 4 summarizes these estimates of the luminosity function of compact galaxies in terms of the Schechter (1976) parameters M^* and α.

How do we interpret these apparently conflicting results? Prandoni et al (1994) have

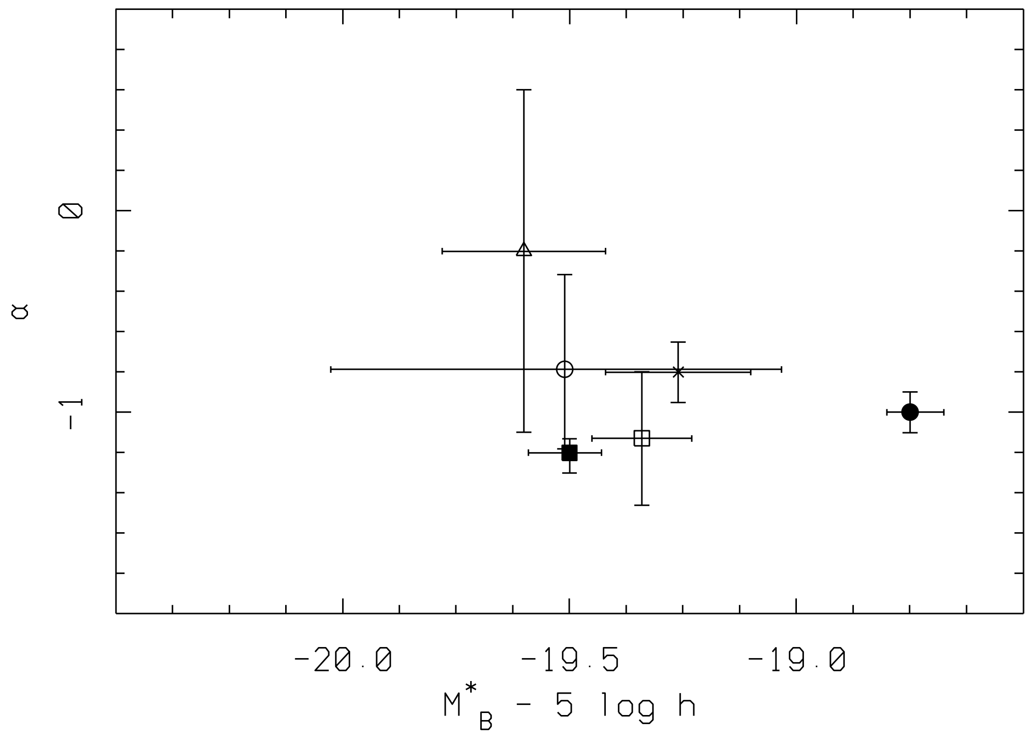

Fig. 4.— Optical luminosity function parameters of compact groups. Triangle: Mendes de Oliveira & Hickson (1991), open square: Sulentic & Rabaça (1994), cross: Ribeirao et al (1994), open circle: mean of the three RSCG samples (Barton et al 1996). For comparison, the filled circle and square indicate luminosity function parameters for galaxies in the CFA-Combined (Marzke et al 1994) and SSRS2 (da Costa et al 1994) surveys respectively, representing galaxies in lower-density environments.

argued that the HCG catalog is biased toward groups with a small magnitude range Δm, because the SCGs have a larger fraction of high Δm groups. However, it is not known what fraction of such groups are physically real, as few redshifts have yet been obtained. Such a bias could affect the luminosity function of Mendes de Oliveira & Hickson (1991), particularly at the faint end, but it is not evident that the bias is sufficient to account for the apparent faint-galaxy deficit. On the other hand, the small sample used by Ribeiro et al (1994) may not be representative of compact groups in general. Hickson (1997) points out that the Ribeiro et al (1994) sample has a spiral fraction of 0.60, substantially higher than that of the whole HCG catalogue, and contains 7 of the 16 HCGs found to be in a high density environment by Palumbo et al (1995). This suggests that the their sample has more than the usual amount of field galaxy contamination. De Carvalho et al (1994), note that the faint galaxies form a more extended distribution than do the brighter galaxies. Thus they may be a dynamically distinct component, or simply unrelated field galaxies. Finally, the redshift-selected RSCG sample also shows mild evidence for a faint galaxy deficiency.

While the faint end of the LF in compact groups appears to be depleted, there is evidence that the bright end may be enhanced. Limber and Matthews (1960) were the first to remark that "the members of Stephan's Quintet are to be classed among the brightest of galaxies". It is possible that this may be in part due to interaction-induced star formation, at least for the spiral galaxies. On the other hand Mendes de Oliveira & Hickson (1991) compared their luminosity function of elliptical galaxies in compact groups with those in the Virgo and Coma Clusters (as reported by Sandage et al 1985 and Thompson & Gregory 1980) and found that that the compact-group ellipticals have a luminosity enhancement of more than 1 mag compared to cluster ellipticals. Sulentic and Rabaça (1994) find a similar enhancement in their morphological-type-specific luminosity function. This suggests that compact group elliptical galaxies may have a unique formation mechanism.

From the luminosity function, one can estimate the contribution of compact groups of galaxies $\mathcal{L}_{CG}$ to the total galaxian luminosity density $\mathcal{L}$. Mendes de Oliveira & Hickson (1991) obtained a ratio of $\mathcal{L}_{CG}/\mathcal{L} \simeq 0.8\%$. Applying the same analysis to the luminosity function of Ribeiro et al (1994) gives a ratio of 3.3%. For the RSCGs, the figure is comparable: for groups of four or more galaxies, Barton et al (1996) obtain a compact group abundance of $1.4 \times 10^{-4} h^{-3}$ Mpc^{-1} which leads to a luminosity density ratio of approximately 3%. These are surprisingly high figures considering the short dynamical times of most compact groups.

5.4. Star formation and nuclear activity

Evidence is accumulating that tidal interactions play an important role in triggering starburst activity in galaxies (eg. Maccagni et al 1990, Campos-Aguilar & Moles 1991, Kormendy & Sanders 1992, Sanders & Mirabel 1996). Compact groups, with their high galaxy density and evident signs of galaxy interaction should be ideal systems in which to study such effects. Many HCGs do in fact contain galaxies showing starbursts or harboring active galactic nuclei (AGN). For example, HCG 16 is found to contain a Seyfert 2 galaxy, two LINERs, and three starburst galaxies (Ribeiro et al 1996). HCG 31 contains five galaxies showing signs of recent starburst activity (Rubin et al 1990, Iglesias-Páramo & Vílchez preprint). Seyfert galaxies are also found in HCG 77, 92, 93 and 96.

The general degree of star formation activity in compact group galaxies can be determined from infrared observations. To date, studies have been based primarily on data from the IRAS satellite. Hickson et al (1989) found sources in 40 HCG from a search of the Point Source Catalog. They concluded that the ratio of far-infrared-to-optical luminosity is greater by about a factor of two in compact group galaxies, compared to that of isolated galaxies. This result was disputed by Sulentic and De Mello Rabaça (1993) who argued that the low spatial resolution of the data made the assignment of infrared flux to individual galaxies ambiguous. They concluded that redistribution of the flux could result in little or no infrared enhancement, a conclusion echoed by Venugopal (1995). However, in cases of doubt, Hickson et al (1989) identified the infrared galaxy on the basis of radio emission. The well-known correlation between infrared and radio continuum emission makes it unlikely that the results are much in error. Analysis of improved data (eg. Allam et al 1996) should soon resolve questions about the identifications and infrared fluxes.

The resolution problem can be avoided by considering the infrared colors of the sources instead of the infrared/optical ratio. Zepf (1993) compared the ratio of 60 μm to 100 μm fluxes of compact group galaxies with those of isolated galaxies and also with those of galaxies believed to be currently merging. He found that the compact group sample was significantly different from both other samples, and estimated that about 1/3 of the compact group galaxies had warm colors (larger 60/100 μm ratios) similar to those of merging galaxies.

Another approach to interpreting the infrared results was taken by Menon (1991) who emphasized that the strong correlation between radio and infrared radiation indicates that these likely originate from a common region. In compact group spirals the radio emission is primarily nuclear whereas in isolated spirals it originates in the disk. If this is also true for the infrared flux, there must be an enhancement of the infrared/optical ratio, in the nuclear region, of more than an order of magnitude. This idea is supported by recent millimeter-wavelength observations (Menon et al 1996) in which CO emission is detected in 55 of 70 IRAS-selected HCG galaxies. The inferred ratio of infrared luminosity-to-H_2 mass showed an enhancement which correlates with the projected nearest-neighbor distance.

Further clues are provided by radio continuum studies. Nonthermal emission from spiral galaxies can arise from both disk and nuclear sources. Disk emission is predominantly due to supernova remnants and is thus related to the star formation rate. Nuclear emission can arise both from star formation and from an active nucleus. Menon (1995) observed 133 spiral galaxies in 68 HCG, and found that overall they typically show less continuum emission than those in isolated environments, which is consistent with the neutral hydrogen observations. However, when considering the nuclear regions alone, the radio emission is found to be an order of magnitude higher compared to isolated spirals. The implication is that star formation and/or AGN activity is substantially enhanced in the nuclear regions of many compact group spiral galaxies. This is generally consistent with a picture in which galaxy interactions remove gas from the outer regions of galaxies, while simultaneously allowing gas to flow inwards toward the nucleus, resulting in enhanced star formation in the nuclear region, and possibly fueling an active nucleus.

Although there is a clear example of tidal interaction stimulating disk radio emission in at least one compact group (Menon 1995a), statistical evidence for a link between interactions and radio emission in compact groups is only now accumulating. If interactions are stimulating nuclear radio emission, one would expect the radio luminosity to be correlated with some index describing the degree of interaction such as the projected distance to the nearest neighbor. Evidence in support of this was found by Vettolani & Gregorini (1988) who observed that early-type galaxies which have a high ratio of radio-to-optical emission show an excess of nearby neighbors. A similar effect was observed by Malumian (1996) for spiral galaxies in groups. Examining compact group galaxies, Menon (1992) found that elliptical and S0 galaxies detected at a wavelength of 20 cm had closer neighbors than the undetected galaxies. The effect was not found for spiral galaxies, but if one considers only the detected galaxies, there is a significant correlation between radio-to-optical luminosity and nearest neighbor distance for both early and late type galaxies (TK Menon, private communication).

Continuum radio emission has also been detected in a number of HCG elliptical galaxies. Unlike those found in cluster ellipticals, the radio sources are low-luminosity and compact. Where spectral indices are available, they indicate that the radio emission arises from an AGN rather than from starburst activity (TK Menon, private communication). In the HCG sample, there is a significant preference for radio-loud elliptical galaxies to be first-ranked optically (Menon & Hickson 1985, Menon 1992). The probability of radio emission does not correlate with absolute luminosity, but instead correlates with *relative* luminosity within a group. Spiral HCG galaxies do not show this effect. Although the tendency of radio galaxies in rich clusters to be first-ranked has been known for many years, it is surprising to find a similar effect in small groups, where the number of galaxies and luminosity range is small, the gravitational potential well is much less clearly defined, and it is unlikely that any individual galaxy holds a central location. The effect of optical rank on radio emission had been previously noted in other small groups by Tovmasian et al (1980) although these authors made no distinction between elliptical and spiral galaxies. It is difficult to imagine any explanation for this result in which the compact group is not a true physical system. It would appear that, regardless of absolute luminosity, only the first-ranked (presumably the most massive in the group) elliptical galaxy can develop a radio source.

5.5. Diffuse light

Stars stripped from galaxies by tidal forces should accumulate in the potential well of the group. and may be detectable as diffuse light. In an early photographic study, Rose (1979) found no evidence for diffuse light in his groups, and was lead to the conclusion that most of his groups must be transient configurations. However, Bergvall et al (1981) were successful in detecting ionized gas and a common halo around a compact quartet of interacting early-type galaxies, and evidence for a common halo in VV 172 was reported by Sulentic & Lorre (1983). Diffuse light can clearly be seen in HCG 94, and has been found in HCG 55 (Sulentic 1987), but Pildis et al (1995b) did not detect any in seven other compact groups. Analysis by Mamon (1986) indicated that while the expected diffuse light should be detectable with modern techniques, it would generally be very faint. Estimates of the total amount of diffuse light in the detected groups are rather uncertain as they depend sensitively on subtraction of the galactic light, and the sky background. Deeper photometry and improved image processing techniques may yet reveal diffuse light in other compact groups (Sulentic 1997).

5.6. Cool gas

The mass and distribution of cool galactic and intergalactic gas, can be obtained from observations of the 21-cm line of neutral hydrogen. The first such study of a large sample of compact groups is that of Williams & Rood (1987) who found a median HI mass of $2.2 \times 10^{10} M_{\odot}$. They concluded that compact groups are typically deficient in neutral hydrogen by about a factor of two compared to loose groups. This effect is consistent with similar deficit in continuum radio emission seen in the disks of compact group spiral galaxies (Menon 1995), and suggests that interactions in compact groups has removed much of the gas from the galaxies. Simulations suggest that in addition to an outflow of gas, inflow also occurs which may fuel nuclear star-formation, as suggested by the strongly-enhanced radio emission seen in the nuclear regions of compact group spiral galaxies (Menon 1995).

High-resolution studies of individual groups (Williams & van Gorkom 1988, Williams et al 1991) showed clearly that the gas is not confined to the galaxies. In two of three groups studied, the radio emission originates from a common envelope surrounding the group and in the third group there are signs of tidal distortion. These results strongly indicate that at least these compact groups are physically dense systems and not chance alignments or transient configurations in loose groups. They also show that many groups have evolved to the point that gas contained within individual galaxies has been distributed throughout the group.

In contrast to the HI results, Initial CO-line observations of 15 compact-group galaxies (Boselli et al 1996) indicated a normalized molecular gas content similar to that of isolated spiral galaxies. However, this result is based on normalizing the flux by the optical area of the galaxy, rather than by the infrared luminosity, and may be biased by the relatively small sizes of compact-group galaxies. Further CO studies, currently in progress, should soon settle this question.

5.7. Hot gas

X-ray observations of hot gas in clusters of galaxies can reveal the amount, distribution, temperature and metallicity of the gas, as well as the relative amount and distribution of the total gravitating mass. Temperature, metallicity (fraction of solar abundance), and bolometric luminosities are estimated by fitting a spectral model, such as that of Raymond & Smith (1977) to the data. X-ray emission from compact "poor clusters" was first reported by Schwartz et al (1980), who concluded that their X-ray properties were similar to those of rich clusters. Using the Einstein observatory, Bahcall et al (1984) first detected X-ray emission from Stephan's quintet. The X-ray map revealed that the emission is diffuse and not centered on individual galaxies. However, we now know that most of this emission is associated with a shock front rather than gas trapped in the group potential well (Sulentic et al 1995). Although several other groups (Bahcall et al 1984, Biermann & Kronberg 1984) were detected by the Einstein observatory, further progress required the improved sensitivity of the ROSAT X-ray observatory.

Pointed ROSAT observations revealed massive hydrogen envelopes surrounding the NGC 2300 group, a bright elliptical-spiral pair with two fainter members (Mulchaey et al 1993), and HCG 62, a compact quartet of early-type galaxies (Ponman & Bertram 1993), and showed that these systems are dominated by dark matter. Subsequent investigations detected X-rays from 18 additional compact groups, either from individual galaxies, or from diffuse gas (Ebeling et al 1994, Pildis et al 1995a, Sarraco & Ciliegi 1995, Sulentic et al 1995). These studies showed that the physical properties of individual systems span a wide range, but that the ratio of gas-to-stellar mass is significantly lower than in rich clusters. Moreover, the detected compact groups all contained a majority of early-type galaxies. No spiral-rich groups were detected (although Mulchaey et al 1996b pointed out that they might be found from QSO absorption spectra). This result is consistent with the fact that X-ray-selected groups (Henry et al 1995) and loose groups (Mulchaey et al 1996a) tend to be spiral poor, and led to the suggestion that spiral-rich compact groups might not be physically dense systems at all.

The most extensive X-ray study of compact groups to date is that of Ponman et al (1996). These authors combined pointed and survey-mode observations of a complete sample of 85 HCGs and detected diffuse emission in 22 groups. They conclude that, when the detection limits are considered, diffuse emission is present in at least 75% of the systems. Significantly, they detected diffuse emission in several spiral-rich groups. In these the surface brightness is lower and the X-ray emission has a lower characteristic temperature, as would be expected given the lower velocity dispersions of spiral-rich compact groups. The diffuse X-ray luminosity was found to correlate with temperature, velocity dispersion, and spiral fraction, but not with optical luminosity. The last result suggests that the gas is mostly primordial and not derived from the galaxies. The correlations with temperature and velocity dispersion appear to be consistent with a single relation for clusters and groups (Figure 5).

The total mass in compact groups typically exceeds the stellar and gas mass by an order of magnitude. Pildis et al (1995) derived baryon fractions of 12-19%. Davis et al (1996) obtains 10-16% for the NGC 2300 group. These are comparable to the fractions found for poor clusters (Dell'Antonio et al (1995) and are about half the typical values found for rich clusters. However, the derived baryon fraction depends sensitively on the radius within which it is measured and on the assumed background level (Henriksen & Mamon 1994). Both the total mass, which is dominated by dark matter, and the gas mass continue to increase with radius. Consequently, both the baryon fraction and the gas fraction are poorly determined.

The contribution of compact groups to the X-ray luminosity function has been

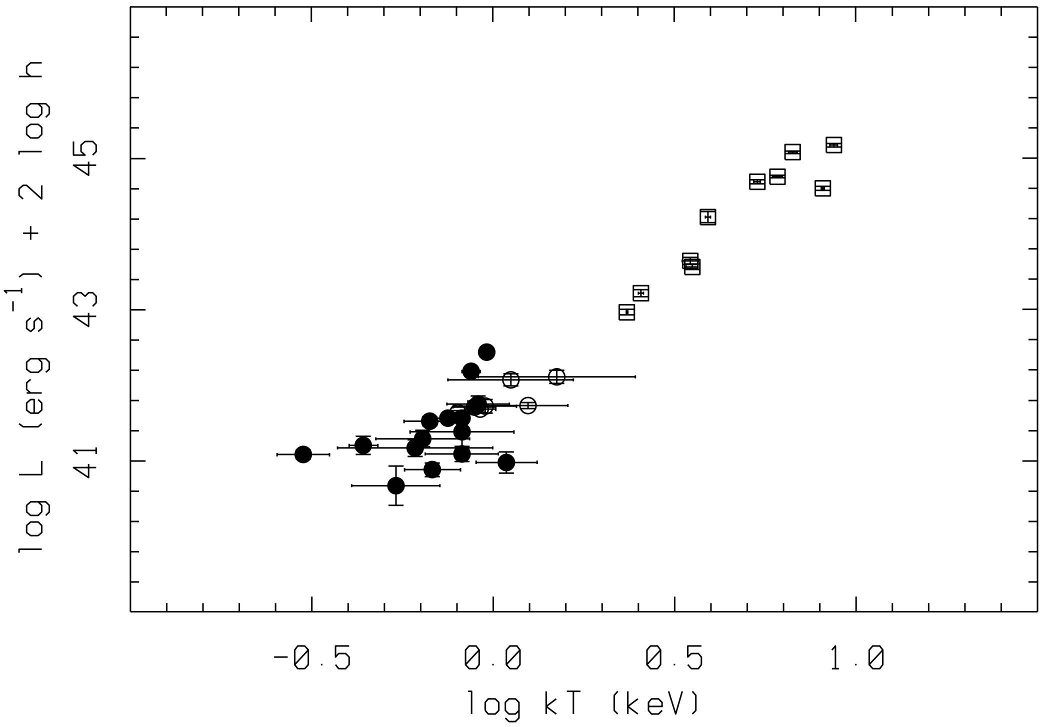

Fig. 5.— Bolometric X-ray luminosity vs temperature. Filled circles indicate compact groups, open circles indicate X-ray selected groups (Henry et al 1995) and squares indicate clusters. X-ray data for the compact groups and clusters are taken from Ponman et al (1996). A single relation is consistent with clusters, groups and compact groups.

estimated by PBEB, who find that on the order of 4% of the total luminosity in the range $10^{41} - 10^{43}$ erg s^{-1} comes from HCGs. This is higher than the contribution of HCG galaxies to the local optical luminosity density estimated at 0.8% by Mendes de Oliveira & Hickson (1991), but it is comparable to the value found by Ribeiro et al (1994).

The metallicity inferred for the X-ray-emitting gas in compact groups is relatively low. PBEB obtain a mean metallicity of 0.18 solar, compared to the value, 0.3-0.4 solar, found in rich clusters. This is comparable to the low value (< 0.11 solar) found for the NGC 2300 group (Davis et al 1996). These figures suggest that the gas is largely primordial, a result supported by the absence of a correlation between X-ray and optical luminosity. However, given the limited spectral resolution of ROSAT, these low metalicities cannot yet be considered secure. The higher spectral resolution and sensitivity of the ASCA satellite should provide more definitive results. Recent observations of HCG 51 and the NGC 5044 group found metal abundances comparable to those of clusters (Fukazawa et al 1996).

6. PHYSICAL NATURE

6.1. Discordant redshifts

The nature of the discordant redshift members of compact groups has been a subject of debate for many years (eg. Burbidge & Burbidge 1961a, Burbidge & Sargent 1971, Nottale & Moles 1978, Sulentic 1983). If the frequency of discordant galaxies is inconsistent with the statistics of chance projection, it might signify the need for new physical theories (Arp 1987), or for gravitational amplification of background galaxies (Hammer & Nottale 1986). Initial estimates of the chance probability of finding discordant galaxies in groups like Stephan's Quintet, Seyfert's Sextet and VV 172, were very small (Burbidge & Sargent 1971). However, such probabilities were recognized to be difficult to determine reliably, because the a priori probability of *any* particular configuration of galaxies is also very small (Burbidge & Sargent 1971). Only with a well-defined sample of groups and a complete characterization of selection effects, can meaningful estimates of the probabilities be made. The explicit selection criteria of the HCG catalog in principal makes this sample suitable for a quantitative statistical investigation of the discordant-redshift question. Sulentic (1987) first concluded that the number of discordant redshifts in the catalog is too large to explain by chance. On the other hand, Hickson et al 1988a and Mendes de Oliveira (1995), applying the selection criteria more rigorously, found no strong statistical evidence for this. Their result, however, may be biased by incompleteness in the HCG catalog: There seem to be too-few low surface brightness groups in the catalog, and the "missing" groups may have a higher fraction of discordant redshifts (Sulentic 1997).

In order to address the incompleteness issue, Iovino & Hickson (1996) combined observational results from both the HCG and SCG catalogs with Monte-Carlo simulations. Their technique exploits the unbiased nature of the SCG catalog and the complete redshift coverage of the HCG sample. They conclude that for all except the two highest-surface-brightness quintets (Stephan's Quintet and Seyfert's Sextet), the number of discordant redshifts is consistent with chance projections. For these two, the chance probabilities are low. However, for both of these systems there is independent physical evidence that the discordant galaxies are at the cosmological distances that correspond to their redshifts and are therefore not group members (Kent 1981, Wu et al 1994).

One should not assume that the situation is now completely settled. Further studies will be possible when redshifts have been obtained for the SCG galaxies. There are still other questions that have not been adequately addressed, such as reported redshift quantization (Cocke & Tifft 1983). However, at this point it appears that the frequency of discordant galaxies does not require a new interpretation of galaxy redshifts. In fact, physical evidence suggests the opposite. The discordant galaxies all have physical properties consistent with a cosmological distance. For example those with higher redshift tend to be smaller and fainter than other members of the group, and vice versa (Mendes de Oliveira 1995).

6.2. Physical association and density

Because we can measure only three phase-space dimensions for galaxies in compact groups (two components of position and one of velocity), the groups are subject to projection effects. Because of this, they may not be physically dense, or even physically related systems.

The following interpretations have so far been suggested for compact groups:

1. transient dense configurations (Rose 1977)
2. isolated bound dense configurations (Sulentic 1987, Hickson & Rood 1988)
3. chance alignments in loose groups (Mamon 1986, Walke & Mamon 1989, Mamon 1995)
4. filaments seen end-on (Hernquist et al 1995)
5. bound dense configurations within loose groups (Diaferio et al 1994, Governato et al 1996)

Evidence for and against physical association and high density in the HCG sample, to 1988, was summarized by Hickson & Rood (1988), and by Walke and Mamon (1989) respectively. Since that time, several new results have emerged. From an analysis of optical images, Mendes de Oliveira & Hickson (1994) concluded that 43% of all HCG galaxies show morphological features indicative of interaction and/or merging, and that 32% of all HCGs contain three or more interacting galaxies. These percentages are likely to rise with more-detailed studies and sophisticated image analysis (Longo et al 1994). This high frequency of interactions observed in compact groups is difficult to reconcile with the chance alignment and filament hypotheses, even if the alignments contain physical binaries (Mamon 1995).

The high fraction of HCGs showing diffuse X-ray emission is very strong evidence that a large fraction of these systems are physically dense, and are not transient configurations or projection effects. Although the exact numbers are not final, due to the faintness of the sources and the problems of contamination by sources associated with the individual galaxies, it seems evident that many groups are dense bound systems. The correlations seen between X-ray and optical properties, and the fact that the X-ray properties of compact groups are not inconsistent with those of clusters reinforces this conclusion.

Ostriker et al (1995) have argued that the relatively low X-ray luminosities of compact groups might not be due to a low gas fraction, but instead could be understood if the groups are filaments seen in projection (Hernquist et al 1995). However, Ponman et al (1996) point out that in order to explain even the fainter compact groups, gas temperatures $T \sim 1$ keV and densities $n \sim 10^{-4}$ cm^{-3} would be required. These appear to be ruled out by both observations (Briel & Henry 1995) and simulations (Diaferio et al 1995, Pildis et al 1996).

Even if compact groups are physically dense, they may not be as dense as they appear. As mentioned in Section 2, a sample of groups selected on the basis of high apparent density will be biased by the inclusion of looser systems which appear more compact due to geometrical or kinematic effects. Is this bias large? Its magnitude can be estimated as follows: Consider n galaxies randomly located within a circle of radius R on the sky. What is the probability $f(x,n)$ that they will fall within some circular subarea of radius xR? The answer can be obtained using analytic expressions derived by Walke & Mamon (1989). From their Equations 1 and 6 (setting $N = n$ and $\mathcal{N}_{ext} = 1$) we obtain

$$f(x,n) = \frac{n!}{\pi^n} \int_0^x dr \int_0^{1-r} d\rho \frac{d\mathcal{N}}{dr d\rho} \tag{1}$$

where

$$d\mathcal{N} = \frac{2\pi^{n-1} n r^{2n-3}}{(n-2)!} 2\pi\rho d\rho dr \tag{2}$$

is the number of possible configurations with radius between r and $r + dr$ and distance from the center between ρ and $\rho + d\rho$. Here we have neglected a small edge contribution that is unimportant for small values of x (Walke and Mamon's case 3). This gives

$$f(x,n) = n^2 x^{2n-2}\Big[1 - 4\frac{n-1}{2n-1}x + \frac{n-1}{n}x^2\Big] \tag{3}$$

Now, an observer would infer a galaxy space density that is higher by a factor $\beta = x^{-3}$, so the average apparent space density enhancement is

$$\begin{aligned} <\beta> &= \int_0^1 \beta \frac{df(x,n)}{dx} dx \\ &= \int_0^1 n^2 x^{2n-5}\Big[1 - 4\frac{n-1}{2n-1}x + \frac{n-1}{n}x^2\Big] dx \\ &= \frac{2n^2(n-1)}{(2n-5)(2n-3)(n-2)} \end{aligned} \tag{4}$$

Thus we expect to typically overestimate the space density by about a factor of 12.0 for triplets (or quartets containing a physical binary), 3.2 for true quartets and 2.0 for quintets.

7. COSMOLOGICAL IMPLICATIONS

7.1. Clustering and large-scale structure

A key question that remains is the position of compact groups in the clustering hierarchy. Are compact groups distinct entities (Sulentic 1987) or an intermediate stage between loose groups and triplets, pairs and individual galaxies (Barnes 1989, White 1990, Cavaliere et al 1991, Rampazzo & Sulentic 1992, Diaferio et al 1994). Some compact groups are purely projection effects, others may be small clusters (Ebeling et al 1995), but most appear to be real. It seems that they can arise naturally from subcondensations in looser groups, but further studies are needed to better determine both the observed space density of groups as a function of population and the timescales involved in the evolutionary process.

This question is related to that of the formation mechanism of compact groups. Two mechanisms have been discussed in the literature. Diaferio et al (1994) conclude that compact groups form continually from bound subsystems within loose groups. This gains some support from the observation (see Section 3) that most HCGs are embedded in loose groups, although it is not obvious that these loose groups are sufficiently rich (Sulentic 1997). Governato et al (1996), proposed a model in which merging activity in compact groups is accompanied by infall of galaxies from the environment. This naturally explains the observed mix of morphological types, and it allows compact groups to persist for longer times.

Where do the Shakhbazian groups fit in this picture? Recent studies (Tikhonov 1986, Amirkhanian & Egikian 1987, Amirkhanian et al 1988, 1991, Amirkhanian 1989, Kodaira et al 1988-91, Stoll et al 1993-1996) show that these objects are typically compact clusters or groups of early-type galaxies. Although the systems were selected on the basis of red colors and compact appearance of their galaxies, both of these factors result from their large distances because K-corrections and contrast effects become significant. The galaxies are in fact relatively normal, although luminous (Del Olmo et al 1995). However, the number of blue (gas rich) galaxies in these systems does seem to be very small. Thus it appears the Shakhbazian groups are mostly small clusters, possibly intermediate in physical properties between classical compact groups and clusters.

7.2. Galaxy evolution and merging

If the groups are dynamically bound, galaxy mergers should commence within a few dynamical times (Carnevali et al 1981, Ishizawa et al 1983, Barnes 1985, Ishizawa 1986, Mamon 1987, 1990, Zheng et al 1993). Both N-body and hydrodynamic simulations indicate that the dark matter halos of individual galaxies merge first, creating a massive envelope within which the visible galaxies move (Barnes 1984, Bode et al 1993). Kinematic studies of loose groups (eg. Puche & Carignan 1991) indicate that the dark matter is concentrated around the individual optical galaxies. In contrast, the X-ray observations indicate that in most compact groups, the gas and dark matter is more extended and is decoupled from the galaxies. This may explain the observation that galaxies in compact groups typically have mass-to-light ratios 30% to 50% lower than more isolated galaxies (Rubin et al 1991).

Is there any observational evidence that galaxies in compact groups are merging? By 1982 it was evident that first-ranked galaxies in compact groups did not appear to be merger products, because the fraction of first-ranked galaxies that are type E or S0 is the same as for the general population of HCG galaxies (Hickson 1982). If mergers were a dominant effect, the first-ranked galaxies would be expected to be more often elliptical. The same conclusion was reached by Geller & Postman (1983) who found that the luminosities of first-ranked galaxies were consistent with a single luminosity distribution for all group galaxies. Of course this may just mean that in small groups the first-ranked galaxy is not necessarily the most evolved. Rather, one should ask if *any* galaxies in compact groups show indications of merging. The relative paucity of merging galaxies in compact groups was first noted by Tikhonov (1987), from a visual inspection of optical images. Zepf & Whitmore (1991) realized that elliptical galaxies formed by recent mergers of gas-rich systems should have bluer colors than normal. Examining the HCGs, they found only a small enhancement in the fraction of early-type galaxies having blue colors, a conclusion reinforced by an independent study by Moles et al (1994). On the other hand, Caon et al (1994) argued that the large effective radii of compact group elliptical galaxies is indicative of an origin by merging or accretion of companions.

Zepf (1993) estimated that roughly 7% of the galaxies in compact groups are in the process of merging. This conclusion was based on roughly consistent frequencies of *(a)* optical signatures of merging, *(b)* warm far-infrared colors, and *(c)* sinusoidal rotation curves. However, few galaxies show all of these effects simultaneously. The merging fraction may thus be as high as 25% if one allows that any one of these criteria would be considered to be sufficient to indicate a merger (Hickson 1997). Given the small numbers of objects in these studies, it is fair to say that the fraction of merging galaxies is highly uncertain at present. It seems safe to conclude that current observations do not rule out a significant amount of merging in compact groups.

Detailed studies of individual compact groups can be quite revealing. Many galaxies that at first appear normal are revealed to have peculiar morphology or spectra when examined more closely. Many, perhaps most, compact groups clearly contain galaxies that are dynamically interacting. However, the groups likely span a range of evolutionary states. At the extreme end are high-density groups like Seyfert's Sextet, HCG 31, HCG 62, HCG 94 (Pildis 1995) and HCG 95 (Rodrigue et al 1995) in which we find strong gravitational interactions. At the other end are lower density compact groups, such as HCG 44, which most likely are in a less-advanced stage of evolution. This picture is supported by radio observations: Seyfert's Sextet and HCG 31 are both embedded in extended HI clouds whereas in HCG 44 the HI is associated with individual galaxies (Williams et al 1991).

It seems clear that the groups as we now see them can persist for only a fraction of a Hubble time. Simulations indicate that merging should destroy the group on a time scale t_m that is typically an order of magnitude larger than t_d, depending on the distribution of dark matter (Cavaliere et al 1983, Barnes 1984, Navarro et al 1987, Kodaira et al 1990) and initial conditions (Governato et al 1991). Assuming that the groups are in fact bound dynamical systems, we can draw two conclusions: *(a)* There must be an ongoing mechanism for forming or replacing compact groups, and *(b)* there must be a significant population of relics of merged groups.

What are the end-products of compact groups? It is tempting to identify them with field elliptical galaxies, following a suggestion first made by Toomre (1977). Simulations

(Weil & Hernquist 1994) indicate that multiple mergers in small groups of galaxies best reproduce the observed kinematical properties of elliptical galaxies. The resulting galaxies are predicted to possess small kinematic misalignments, which can be detected by detailed spectroscopic and photometric studies. Neverthess, it remains to be demonstrated that these merger remnants can reproduce the tight correlation between size, luminosity and velocity dispersion found in present-day elliptical galaxies.

If compact groups have lifetimes on the order of t_m, and form continuously, then the number of relics, per observed group, is expected to be on the order of $(H_0 t_m)^{-1}$. Thus, the number of relics could exceed that of present day groups by as much as an order of magnitude. Mamon (1986) estimated that, if all HCGs are real, then the relics would account for about 25% of luminous field elliptical galaxies. As we have seen, the true space density of compact groups is uncertain by at least a factor of two, and may be underestimated because of selection biases. There is then the potential problem of producing too many relics.

A second problem is the fact that the integrated luminosities of compact groups are typically a factor of three to four times greater than luminosities of isolated elliptical galaxies (Sulentic and Rabaça 1994). It is possible that interaction-induced star formation has boosted the luminosities of some compact-group galaxies, and that some degree of fading of the merger product is expected. However, at this point it is not clear whether or not the relics can be identified with isolated elliptical galaxies.

Despite these problems, a fossil compact group may have actually been found. Ponman et al (1995) have detected a luminous isolated elliptical galaxy surrounded by diffuse X-ray emission which is consistent with the expected end-product of a compact group. If more objects like this are found, it may be possible to compare their space density with that expected for compact group relics.

7.3. Role in galaxy formation and evolution

Interactions are often implicated in the development of active nuclei in galaxies (eg. Freudling & Almudena Prieto 1996). The HCG catalog includes several examples of compact groups containing both starburst galaxies and AGN. Several recent examples of associations between starburst galaxies or AGN and what appear to be compact groups have been reported: Del Olmo & Moles (1991) have found a broad-line AGN in Shakhbazian 278; Zou et al (1995) find that the luminous infrared source IRAS 23532 coincides with a compact group that includes a Seyfert 1 as well as a starburst galaxy. If this association extends to QSOs, one would expect to find numerous compact groups at redshifts $z \sim 2$, where the comoving number density of QSOs peaks (eg. Hartwick & Schade 1984). The tendency for QSOs to have close companions has been known for some time (eg. Stockton 1982, Bahcall et al 1997). Recently, several examples of compact groups associated with luminous infrared galaxies, AGN and QSOs at $z \simeq 2$ have been found using HST (Pascarelle et al 1996, Francis et al 1996, Matthews et al 1994, Tsuboi & Nakai 1994, Hutchings 1995, Hutchings et al 1995).

These observations provide support to the idea that tidally-triggered star formation is a predominant factor in the galaxy formation process (Lacey & Silk 1991, Lacey et al 1993). In this model disk star formation occurs relatively late, after the compact group has formed and tidal interactions are strong. This seems at least qualitatively consistent with the fragmentary nature of high-redshift galaxies observed with the Hubble Space Telescope (Schade et al 1995), although these fragments appear to be much less luminous and more irregular than most present-day compact group galaxies. The model also offers a possible explanation for the excess numbers of faint blue galaxies found in field galaxy count as dwarf galaxies undergoing star formation at a redshift of $z \simeq 1$.

Compact groups may possibly play a role in the formation of other systems. We have seen that giant galaxies may be formed as the end product of compact-group evolution. At the other end of the scale, dwarf galaxies have physical properties distinct from normal galaxies, which suggests a unique formation mechanism. One possibility is that they form during gravitational interactions from tidal debris (Duc & Mirabel 1994). If this is the case, one would expect to find evidence for this in compact groups of galaxies. From an examination of condensations in tidal tails, Hunsberger et al (1996) concluded that the fraction of dwarf galaxies produced within tidal debris in compact groups is not negligible. There is also evidence that star clusters form from tidal debris. Longo et al (1995) have found an excess population of unresolved blue objects around HCG 90 which appear to be recently formed star clusters. These may be similar to the population of new star clusters recently reported in the merger remnant NGC 7252 (Whitmore et al 1993).

7.4. Gravitational lensing

Because compact groups have a high galaxy surface density, they may form effective gravitational lenses. Gravitational amplification of background field galaxies was proposed by Hammer and Nottale (1986) as a possible explanation for the presence of the high-redshift discordant member of this group. Mendes de Oliveira and Giraud (1994) and Montoya et al (1996) find that most HCGs are too nearby to produce strong lensing effects. However, because the critical mass density required for strong lensing depends reciprocally on distance, analogous systems 5-10 times more distant should produce a non-negligible fraction of giant arcs.

7.5. Cosmology

Studies of small groups may provide clues to the overall structure of the universe. The baryon fractions found in clusters of galaxies appear to be inconsistent with a density parameter $\Omega = 1$, unless the dark matter is more prevalent outside clusters (White 1992, Babul & Katz 1993). Compact groups provide a means to study dark matter in such regions. The baryon fractions found for compact groups do appear to be lower than those for clusters. David et al (1995) argued that the gas is the most extended component; galaxies being the most compact and the dark matter being intermediate. They concluded that the baryon fraction approaches 30% on large enough scales, which is comparable to the values found for clusters. Given the constraints of standard Big-Bang nucleosynthesis this would imply that the density parameter Ω is at most 0.2. On the other hand, the infall picture of compact-group evolution (Governato et al 1996) requires a high-density $\Omega \sim 1$ universe. In a low-density universe the infall rate is insufficient. As there is at present no other clear mechanism for avoiding the overproduction of relics by merging compact groups, this may be a strong argument for a high-density universe.

During the last two decades we have seen a resurgence of interest in compact groups. While initially little more than a curiosity, these systems are now viewed as potentially important sites of dynamical evolution, shaping the structure of many galaxies. It now seems clear that while many compact groups are contaminated by projections, a large fraction of at least the high-surface-brightness HCGs are physically dense. They form by gravitational relaxation processes within looser associations of galaxies. The densest are generally in an advanced stage of evolution characterized by strong interactions, starburst and AGN activity, stripping of stellar and dark matter halos, and merging. They contain large amounts of dark matter and primordial X-ray-emitting gas trapped within the gravitational potential well.

Despite this progress, many questions remain unanswered. What are the end products of compact group evolution, and do they have properties consistent with any know population of objects? What is the space density of such relics? Where do compact groups fit in the overall clustering hierarchy? What is their role in the evolution of galaxies both past and present? Given the current interest and research activity in this area, it is likely that many of these questions may soon be addressed.

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