

**eea.iop.org**

DOI: [10.1888/0333750888/1671](https://doi.org/10.1888/0333750888/1671)

# **Groups of Galaxies**

**Joshua E Barnes**

From

**Encyclopedia of Astronomy & Astrophysics**

**P. Murdin**

© IOP Publishing Ltd 2006

ISBN: 0333750888

**IOP**

**Institute of Physics Publishing  
Bristol and Philadelphia**

Downloaded on Tue Feb 07 18:37:09 GMT 2006 [131.215.103.76]

[Terms and Conditions](#)

## Groups of Galaxies

Gravity creates a huge variety of cosmic structure, but most galaxies are found in groups of no more than a few dozen members. Groups range from the satellite systems of giant galaxies to loose associations a few times denser than their surroundings to compact cores of rich galaxy clusters. The common thread linking these examples is that the galaxies making up a group interact more with each other than they do with the rest of the universe; thus a group is a dynamical unit.

Groups are important for the evolution of galaxies and of large-scale structures. GALAXY FORMATION appears to be a drawn-out process, involving the collapse of primordial perturbations, accretion of gas and dark matter, outright merging of distinct objects and outflows of gas enriched by supernovae. Most galaxies conduct these transactions in group environments. However, group environments are unstable; while the galaxies in a group are forming, the group itself may be separating out from the cosmic expansion, collapsing under the influence of gravity, accreting new members and finally merging with other groups to build clusters and superclusters.

We can study the present outcome of these ongoing processes in our immediate vicinity and glimpse some earlier stages at high REDSHIFT. However, reconstructing the evolution of groups is a difficult problem. Two powerful tools which complement optical studies are computer simulations and multiwavelength observations. Simulations model the key dynamical ingredients of groups, including the DARK MATTER IN GALAXIES which is otherwise inaccessible. Observations at radio and x-ray wavelengths show how intergalactic gas responds as groups evolve.

### Evolutionary stages

Figures 1 through 4 show four groups, ordered by stage of development. Group evolution begins when a bound configuration of several galaxies collapses out of the Hubble flow; the LOCAL GROUP (LG) is now at this stage, with the Milky Way (MW) and M31 approaching each other for the first time (figure 1). One of our nearest neighbors, the M81 group (figure 2), illustrates a more advanced stage; as the HI image shows, three galaxies are linked by a complex structure indicating that they have already undergone at least one passage. STEPHAN'S QUINTET (figure 3), a compact group, contains an extended, possibly tidal feature in neutral hydrogen and a central cloud of hot gas visible in x-rays; this gas may have been heated by a fast, interpenetrating encounter between two galaxies. Finally, V Zw 311 (figure 4) is actually the core of cluster Abell 407; it is likely that several of these galaxies will merge over the next  $\sim 1$  Gyr.

These four examples represent not only different evolutionary stages but also different evolutionary *tracks*. For example, the LG will become more compact as the MW and M31 draw closer, possibly evolving into a system like the M81 group, but probably not attaining the dramatic status of Stephan's Quintet, let alone V Zw 311.

### Collapse

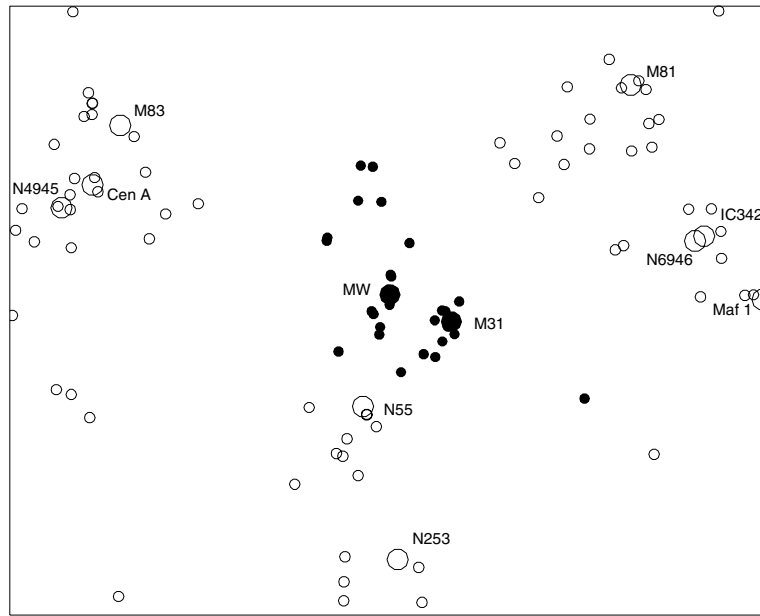
The LG (figure 1) is probably the best place to study a collapsing group. Most of its luminosity is associated with the MW and M31, which are currently separated by  $\sim 0.73$  Mpc and approaching each other at  $120 \text{ km s}^{-1}$ . A simple model treats the main galaxies as point masses moving along a linear orbit—an ellipse of zero width. In this approximation, the two galaxies coincided at the big bang  $t_0 \simeq 13$  Gyr ago, separated smoothly with the Hubble flow, reached a maximum separation of  $\sim 1$  Mpc some 5 Gyr ago and are now falling together. To account for this history, the LG's total mass must be about  $4 \times 10^{12} M_\odot$  and its mass-to-light ratio  $M/L_V \simeq 100$ . This is several times most estimates of the MW's  $M/L$  ratio, a sign that unseen dark matter is important in extragalactic dynamics.

Thus it seems that much of the LG's mass resides in structures larger than individual galaxies. Cosmological  $N$ -body simulations show that gravity deforms a smooth distribution of dark matter with a plausible spectrum of density fluctuations into a complex web of 'pancakes' and filaments; this web constantly evolves as ever-larger scales break away from the Hubble expansion. Halos of dark matter form at the intersections of filaments and grow as mass flows along the filaments. In this picture, the MW and M31 are presumably linked by a major filament and are 'sucked together' as this filament collapses.

### Spins and swings

In gravitational clustering, galaxies acquire their spins from tidal torques. At early times, the material which eventually forms a galaxy has an irregular shape, and as density fluctuations grow this material feels a torque due to the tides of other proto-galaxies. Groups seem natural places to apply this scenario; for example, it has been argued that the MW and M31 are mutually more or less edge-on because each provided the tidal torque which spun up the other. The further assumption that the total spin and orbital angular momentum of the LG is zero then yields a definite prediction for the M31's transverse motion with respect to the MW.

This simple calculation is less plausible on closer inspection. First, in a tally of angular momentum, spins are less important than satellite orbits; for example, the LARGE MAGELLANIC CLOUD's orbit about the MW has several times the angular momentum of the MW's spin, and the same may be true for M31 and M33. Second, the external torque on the MW–M31 binary due to the nearby galaxies shown in figure 1 is sufficient to give the pair a transverse velocity of at least  $\sim 40 \text{ km s}^{-1}$ . This orbital swing completely dominates the total angular momentum of the LG; clearly the LG's dynamical isolation is very imperfect. It is possible that MW and M31 set each other spinning, but the reflex torque on their relative orbit is tiny compared with the torques due to surrounding galaxies. Tests of the tidal torque hypothesis based on auditing the angular momentum of the LG seem doomed to founder on this complication.



**Figure 1.** The LG (filled circles) and other nearby galaxies (open circles). Luminous galaxies (large circles) are labeled. (Courtesy B Tully.)

#### *Least-action models*

To investigate the effects of surrounding galaxies in greater detail requires more than two free-falling bodies. An elegant approach minimizes the action of a system of point-like galaxies subject to mixed boundary conditions: peculiar velocities vanish as  $t \rightarrow 0$ , and all galaxies reach their observed positions at the present. This approach assumes that each galaxy's trajectory and gravitational field are adequately reproduced by a single particle. However, it also admits a rather strong test; given the present masses and redshift-independent distances of galaxies, it predicts their redshifts.

When applied to the LG this method yields impressive agreement between predicted and observed redshifts. Plausible solutions, in which the MW and M31 approach each other for the first time, assign the LG a total mass consistent with the simple two-galaxy estimate above. However, the transverse velocity of M31 depends sensitively on the volume simulated, growing to several hundred  $\text{km s}^{-1}$  when the other galaxies in figure 1 are included; indeed, it is possible that yet more distant galaxies may further modify the solutions. These results, if correct, completely rewrite the past and future of the LG; the MW and M31 are no longer partners in a dance lasting aeons but 'ships passing in the night' at several times their escape velocity. PROPER MOTIONS for M31 and other LG galaxies would settle the issue.

#### **Virial equilibrium**

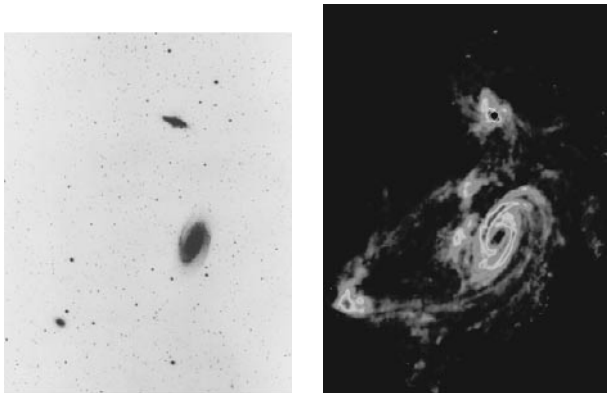
Simple models assume that bound groups reach a quasi-equilibrium state in which galaxies have isotropic orbits with random phases. This state of randomized grace

results from scattering of galaxies by each other and by masses outside the group. However, when do these scatterings occur? If a group is isolated and remains fairly spherical then its constituent galaxies are not deflected from their radial trajectories until the group has collapsed to a small fraction of its maximum radius. In this case the collapse is fairly violent, and the new-born group first reaches equilibrium at  $\sim 200$  times the mean cosmic density. At the opposite extreme in which a nascent group is strongly influenced by surrounding objects the collapse is gentle and the group attains equilibrium at only  $\sim 30$  times the mean density. This is basically the same set of alternatives considered in the discussion of the LG.

Once a group is in equilibrium, a time-averaged version of the *virial theorem* applies:  $2\langle T \rangle + \langle U \rangle = 0$ , where angle brackets denote time averages and  $T$  and  $U$  are the kinetic and potential energy of the group, respectively. Of course, these time-averaged quantities cannot be determined observationally; instead, we observe an ensemble of groups and use orbital randomness to justify taking ensemble averages. Observable quantities include the mean harmonic radius of the group,  $r_h$ , and the line-of-sight velocity dispersion,  $\sigma$ . These parameters may be used to check that group has actually had time to reach virial equilibrium. The collapse time for an isolated, spherical group is approximately the Keplerian period of a particle at the edge of the group, or  $\sim 2.9t_c$ , where

$$t_c = \frac{2r_h}{\sqrt{3}\sigma} \quad (1)$$

is the *crossing time*. Starting from the big bang, it takes a group about one collapse time to reach equilibrium, so a



**Figure 2.** The M81 group in (left) visible light and (right) neutral hydrogen. (Courtesy M Yun.)

reasonable criterion might be  $3t_c < t_0$ . This limit is stricter than necessary for groups which are strongly influenced by neighboring masses, since such groups attain equilibrium with little or no collapse.

In view of the evidence for dark matter in the LG and in rich galaxy clusters, much effort has been devoted to measuring the masses of bound groups. For groups in equilibrium, the virial theorem provides an estimate of the dynamical mass,

$$M_d = \frac{6\sigma^2 r_h}{G}. \quad (2)$$

Group mass-to-light ratios obtained using this approach generally show a wide scatter about a median value of several hundred. Some of this scatter represents fluctuations around virial equilibrium. However, a far larger and more systematic uncertainty arises in assigning galaxies to groups; if  $M_d$  is to provide meaningful group masses, the procedures used to identify groups must be carefully calibrated.

### Catalogs and parameters

In the days before redshift surveys, groups were identified by noting galaxies with similar positions, apparent distances, and other signs of association. This subjective process produced accurate membership lists for nearby groups (e.g. figure 2), but contamination by foreground and background galaxies became much more serious at larger distances. As more redshifts became available it became clear that some ‘traditional’ groups extend along the line of sight for many Mpc; in such cases, a virial analysis is useless since  $\sigma$  reflects Hubble expansion instead of internal dynamics.

Redshift surveys down to a fixed limiting magnitude are probably the best available starting point in constructing group catalogs. However, redshifts reflect peculiar motions as well as Hubble expansion, and this distorts the galaxy distribution deduced from redshift surveys. Consequently, algorithms for group finding cannot treat radial and transverse directions on the same footing. Most

group-finders use a ‘friends of friends’ algorithm which links two galaxies if their projected separation and line-of-sight velocity difference are less than some cutoff values; each set of galaxies linked either directly or via intermediaries defines a group.

The velocity cutoff strongly influences the resulting catalogs; if it is too high then unrelated galaxies along the line of sight may be linked together, while if it is too low then *bona fide* groups may be broken up. The same velocity information is used to define groups and to calculate their velocity dispersions, so it is no surprise that dispersions are also sensitive to the velocity cutoff. Tests run on simulated redshift surveys derived from cosmological  $N$ -body experiments offer some guidance in selecting distance and velocity cutoffs that produce reasonable group catalogs.

A typical catalog generated in this manner links about half of all galaxies into groups. Most groups have three or four members, while a small fraction are much richer. The median density of such groups is about 100 times the background density, and about half the groups have crossing times short enough to be virialized. The mass-to-light ratios derived for these groups are roughly consistent with the value obtained for the LG.

### Dynamical evolution

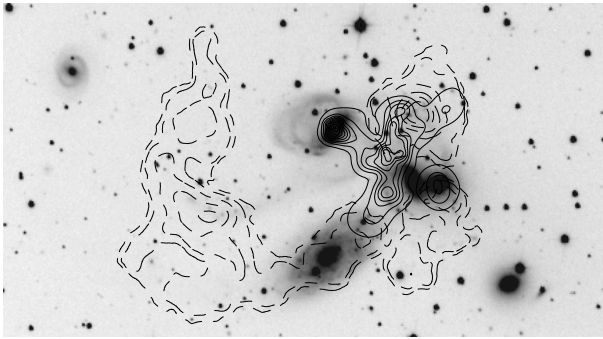
It has been convenient so far to treat groups as systems of point-like galaxies. However, in reality galaxies are not points, and groups may have a good deal of dark matter not associated with individual galaxies. This can have dramatic consequences. For example, virial equilibrium is at best a temporary condition; in the long run, an isolated group cannot attain true equilibrium until all its galaxies coalesce to form a single group remnant.

#### *Galactic encounters*

Thanks to their finite sizes, galaxies are subject to tides. Galaxies in close proximity are simultaneously stretched and squeezed by tidal forces. DISK GALAXIES respond by forming dramatic bridges and tails of stars and gas which reflect the effects of tides on rotationally supported disks; ELLIPTICAL GALAXIES, supported by random motions, may exhibit distended envelopes and off-center isophotes. The explanation of such features as relics of tidal interactions was a key step in understanding the peculiar morphologies of colliding galaxies.

Groups of galaxies are likely sites for tidal interactions. Simple estimates and detailed simulations indicate that in a typical group there is roughly one close encounter per crossing time. A curious feature of tidal interactions is that slower encounters do more damage; groups have relatively low velocity dispersions, so most encounters in groups are slow enough to produce rather spectacular effects.

One example of tidal interactions is shown in figure 2. Even before the HI observations there were signs that the two brightest galaxies in this group were interacting; evidence included the ‘grand design’ spiral of M81 and an

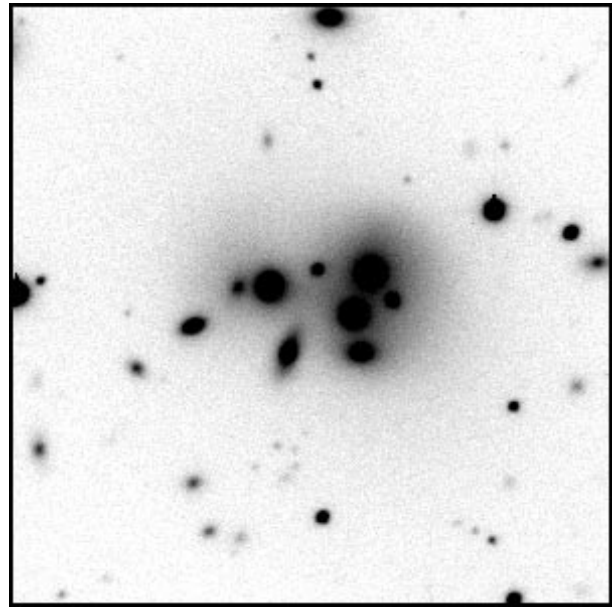


**Figure 3.** Stephan's Quintet, a compact group of galaxies. Plotted on top of the optical image (courtesy M Moles) are thin contours of HI emission (courtesy B Williams) and thick contours of x-ray emission (courtesy H Ebeling). The large spiral galaxy at the bottom is a foreground object.

'explosion', now recognized as a burst of star formation, in M82. The HI maps reveal complex filaments linking these galaxies as well as the third most luminous member, NGC 3077. These structures appear to be bridges and tails extracted from the extended gas disks of the individual galaxies by tidal forces during a fairly recent triple encounter; this encounter may represent the initial collapse of the M81 group.

Tidal interactions are common in COMPACT GROUPS OF GALAXIES where three or more galaxies are seen in near proximity. Besides tidal signatures similar to those already described, many disk galaxies in such groups have asymmetric rotation curves or other unusual kinematic features. Such kinematic peculiarities are among the first signs of a tidal interaction; bridges and tails develop later as perturbed stars drift away from their parent disks.

A compact group with a rather complicated history is shown in figure 3. This is Stephan's Quintet, discovered in 1877. As often happens, not all the galaxies are the same distance; in this case, the largest spiral is a foreground object, while the other five galaxies, including the small spiral on the left, are associated. Of these five, two exhibit tidal tails and other signs of interactions. However, tides are not the only forces at work here—velocity fields of both neutral and ionized hydrogen reveal *two* components separated by at least  $700 \text{ km s}^{-1}$ , while x-rays show a cloud of hot gas at the center of the group. The data suggest that gas is heated by a high-velocity shock between two distinct streams of tidal material, with further energy input from localized formation of massive stars. If so, at least two tidal encounters are required, since the debris of a single passage generally separate at roughly the encounter velocity. Moreover, the large shock velocity implies a deep potential well associated with one or more massive dark halos. Finally, the hot gas responsible for the x-ray emission points to a long-term change, since such gas, once heated, is slow to cool off.



**Figure 4.** 'The once and future cD', V Zw 311, is a complex of galaxies at the center of a poor cluster (courtesy D Schneider).

#### *Orbital decay*

Another consequence of extended mass distributions in groups is the decay of galactic orbits. Tidal encounters between galaxies cause significant orbital decay—roughly speaking, the work required to raise tidal features of visible stars and of dark matter comes from the relative motion of the participants. Two equally matched galaxies whose halos interpenetrate after falling from a great distance will never return to anything like their maximum separation, but will pass even closer the next time around, and merge after a few orbits. This decay is slower in unequally matched encounters, but no less inexorable; it represents a one-way process, a randomization of the ordered relative motions of two galaxies. A similar process occurs when a galaxy orbits within the common halo of a larger group. In the limit where the group halo is much more massive than the galaxy this process can be described by several analytic approximations, none perfect yet all predicting that the galaxy will spiral inward after some  $M/m$  orbits, where  $M$  is the mass of the group and  $m$  is the mass of the galaxy.

Orbital decay can have dramatic consequences in extremely compact groups like the one in the center of V Zw 311 (figure 4). Here we see nearly a dozen early-type galaxies embedded in a common envelope of comparable total luminosity. The velocity dispersion of this group is  $\sigma \simeq 600 \text{ km s}^{-1}$ , while the brighter group members have velocities within  $\sim 200 \text{ km s}^{-1}$  of the mean. Assuming this system is bound, its virial mass is about 10 times the total mass of the visible galaxies, and the unseen material is probably more extended than the luminous envelope. If the brighter galaxies are now on roughly circular orbits,

they will spiral toward the center and presumably merge in  $\sim 1$  Gyr.

While objects as extreme as V Zw 311 are fairly rare, orbital decay occurs in both loose and compact groups. Numerical simulations in which galaxies and dark matter are represented using many thousands of particles are the most reliable way to follow the decay of galactic orbits. Such simulations show that galaxies spiral inward about as fast as predicted by the analytic models. The orbital decay timescale depends on the initial set up, being shorter if most of dark mass is associated with individual galaxy halos and longer if most of the dark mass is invested in a common group halo. However, unless the initial conditions are somehow fine-tuned, the orbits of massive galaxies shrink quite noticeably with each revolution.

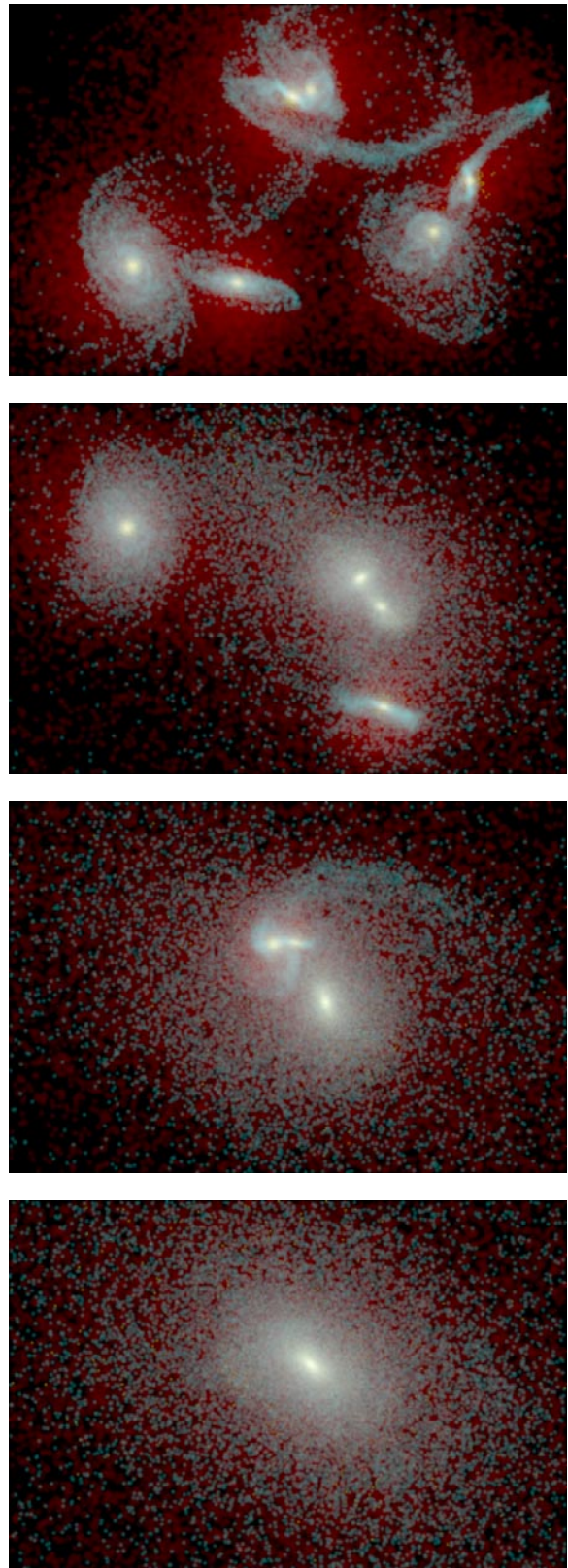
In view of this relentless evolution, one might wonder whether it is correct to estimate group masses using the virial theorem. Numerical studies show that the systematic non-equilibrium effects are fairly modest; on the average, galaxies move about as fast as they would if their orbits were not decaying, and the virial theorem yields consistent mass estimates. However, as galaxies spiral in they explore less and less of the group's potential well, and any mass which lies beyond the region they sample will not be detected by a virial analysis.

#### Mergers

When galaxies spiral toward the center of a group it also becomes more and more likely that they will capture each other and merge. Merging can be described as a combination of orbital decay and tidal disruption. As two or more galaxies undergo successively closer passages, they are tidally stripped from the 'outside in'; most of the stripped material remains bound to the merging system and forms the body of the resulting merger remnant.

The outcome of a merger depends on the participants. Much attention has focused on the hypothesis that elliptical galaxies form by mergers of spiral galaxies. This suggestion is supported by observations of 'twin-tailed' merger remnants which have luminosity profiles and kinematic properties resembling bright elliptical galaxies and by numerical experiments which detail the mechanics of such catastrophic transformations. Together with the companion hypothesis that violent encounters can trigger bursts of star formation, merging succeeds in linking normal and peculiar galaxies into a coherent evolutionary scheme (see GALAXIES: INTERACTIONS AND MERGERS). Yet it is unlikely that all ellipticals resulted from mergers of equal-mass spirals. Some elliptical galaxies may have had multiple bursts of star formation, while others seem more thoroughly 'scrambled' than typical spiral-spiral mergers. If these objects originated in multiple mergers, they probably did so in group environments.

There are many groups with recent or ongoing mergers. One example is the loose, spiral-rich group containing Cen A, a peculiar elliptical galaxy with an active nucleus (see NGC 5128/CENTAURUS A). The dark bisecting dust lane, subtle 'shells' superimposed on the luminosity



**Figure 5.** Numerical simulation of a compact group. These frames span an interval of  $\sim 3$  Gyr.

profile, unusual kinematics revealed by planetary nebulae and irregular structure of its extended envelope all suggest that Cen A swallowed a good-sized gas-rich companion  $\sim 1$  Gyr ago. Another example is the small group of four galaxies including NGC 3921, a classic twin-tailed remnant of a recent merger between two disk galaxies of comparable mass. A third example is Hickson Compact Group 95, in which two smaller spirals appear to be simultaneously merging with a larger elliptical galaxy.

In the case of V Zw 311 (figure 4), the extended envelope surrounding the galaxies probably represents material stripped in the early stages of the merging process. Further stripping as the galaxies sink toward the center of the group will liberate more material, building the merger remnant from the outside in. Once the larger galaxies finish merging, V Zw 311 will contain a very luminous central galaxy with an extended envelope; the expected parameters of this object suggest that we are witnessing the formation of a 'cD' galaxy similar to those which dominate the central regions of many galaxy clusters.

A numerical simulation illustrating the later stages of orbit decay and merging is presented in figure 5. This experiment started with a compact near-equilibrium configuration of six disk galaxies, each surrounded by a modest dark halo. The first frame shows the system shortly before two pairs merge; note the twin-tailed morphology of the pair at the top. Later frames show a further merger of the two remnants, a violent interaction between the composite remnant and the two remaining disk galaxies, and the final remnant, which resembles an elliptical galaxy. Scaling the initial disk galaxies to the MW, the group starts with a diameter of  $\sim 120$  kpc and takes about 3 Gyr to completely merge.

In absolute terms, the merger rate in a loose group is a good deal lower than in a compact group. However, this difference is largely due to the long crossing times of loose groups; within broad limits, there is about one merger per crossing time in loose and compact groups alike. Since loose groups are a good deal more common than compact ones, they probably dominate the net merger rate. Demographic estimates show that while galaxies in compact groups are  $\sim 20$  times more likely to undergo violent interactions and mergers, only one merger in four occurs in a compact group. The timescale for a typical loose group to merge is several times the age of the universe; nonetheless, a modest fraction of galaxies in loose groups have probably undergone multiple mergers.

Where are the relics of group mergers to be found? Some compact groups seem to be truly isolated, and the remnants of such groups should appear as bright, isolated elliptical galaxies. A small number of possible fossils have now been identified; these galaxies typically have extended halos of hot, x-ray-emitting gas similar to those seen in compact groups and poor clusters. However, while ongoing merging in groups has been building up the population of merger remnants, gravitational clustering has been incorporating these remnants into new groups

and larger structures. Even today we find groups 'caught in the act' as they fall together and coalesce to form clusters. Once incorporated into clusters, galaxies are less likely to merge since their encounter velocities are now too high for tidal capture; if cluster ellipticals formed by merging, they can only have done so before the clusters themselves had collapsed. Elliptical galaxies in clusters may have formed in dense groups at redshifts  $z \sim 2$ ; if so, compact groups are the low-redshift analogs of the birthplaces of cluster ellipticals.

#### Bibliography

- Barnes J E 1989 Evolution of compact groups and the formation of elliptical galaxies *Nature* **338** 123–6
- Binney J and Tremaine S 1987 *Galactic Dynamics* (Princeton: Princeton University Press)
- Nolthenius R and White S D M 1987 Groups of galaxies in the CfA survey and in cold dark matter universes *Mon. Not. R. Astron. Soc.* **235** 505–30
- Peebles P J E 1994 Orbits of the nearby galaxies *Astrophys. J.* **429** 43–65
- Raychaudhury S and Lynden-Bell D 1989 Tides, torques and the timing argument *Mon. Not. R. Astron. Soc.* **240** 195–218

Joshua E Barnes