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The Epoch of Galaxy Formation*

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Abstract

Observations of merging and active galaxies at redshifts less than one suggest that galaxy formation is an ongoing process. Cosmological *N*-body models and analytic estimates of the collapse times of large galaxies suggest that the first systems to form probably did so at redshifts less than 4. The theoretical picture that leads to these estimates of the beginning of the formation epoch may be seriously in error if new observations of high redshift galaxies reveal a pre-existing old stellar population.

1. Introduction

The cosmic microwave background fluctuations on the scales relevant to galaxies are smaller than one part in 10^4. From these 0.01% fluctuations, galaxies grew to overdensities of order 1000 sometime between $z = 0$ and $z \sim 10000$. In this paper we will discuss several observational and theoretical constraints on the epoch of formation. Section 2 will discuss observations at small redshifts. In Section 3 we will outline constraints on the formation epoch based on the typical collapse times of large galaxies and in Section 4 we will examine new observational data that may be in conflict with the conventional theoretical picture.

2. Observations of Evolving Galaxies at $z < 1$

Many nearby galaxies are currently going through major structural changes. The work of the Toomres (1972) on tidal encounters between disk galaxies led Alar Toomre (1977) to conclude that galaxies are severely decelerated in close encounters. This rapid deceleration combined with the transient nature of tidal tails means that the many examples of tidal encounters we see today must be accompanied by a much larger number of systems that merged some time ago. Stellar shells around ellipticals are a natural consequence of large galaxies swallowing small satellites (Quinn 1984). The abundance of shell galaxies (Schweizer 1982) implies that most large ellipticals have suffered at least one shell forming event in their lifetime. Similarly the formation of counter-rotating cores in ellipticals (Jedrzejewski and Schechter 1988; Balcells

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and Quinn 1990) and the thick, old disk components in spirals (Gilmore and Wyse 1987; Quinn and Goodman 1986) all argue that both spirals and ellipticals have undergone a rain of matter over a Hubble time. The optical observations of actively star-forming galaxies identified by the IRAS spacecraft have revealed that many bursts of star formation are triggered by galactic tidal interactions (Lonsdale *et al.* 1983). Models of the spectrum of density perturbations in the early universe suggest that initial conditions in which large systems are built up from small lumps give rise to structures that match closely those observed. If this is the case, a merger history is a natural consequence of the cosmological initial conditions. Indeed, the low specific angular momentum content of ellipticals compared with spirals (Fall 1982) suggests that ellipticals were formed by mergers in a lumpy protogalactic environment (Zurek *et al.* 1988).

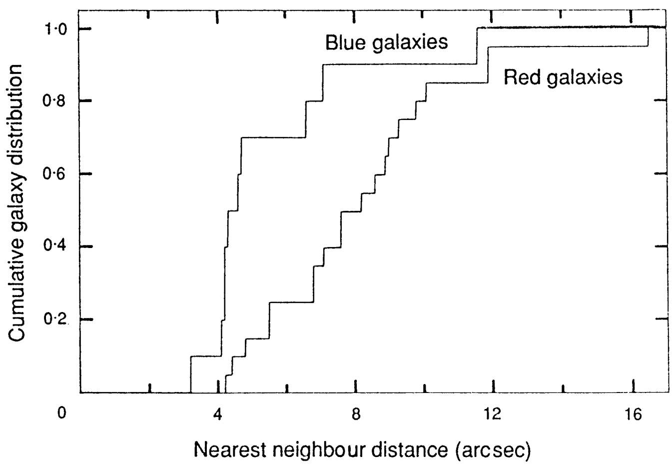


Fig. 1. The number of red and blue galaxies in clusters that show the Butcher-Oemler effect as a function of the distance from their nearest neighbour galaxy (from Lavery and Henry 1988). It would appear that the blue, actively star-forming galaxies are those which are suffering tidal encounters with nearby galaxies.

All of the above pieces of theoretical and observational evidence point towards galaxies being in a state of flux even at low redshifts. Both bursts of star formation and major structural changes are associated with galactic interactions. So galaxy formation is an ongoing process that is still producing 'new' galaxies from preexisting component systems of stars and gas. Were these interactions happening at a greater rate in the past or has the evolution slowed to the point where most galaxies are now fully formed? The Butcher-Oemler (1978) effect suggests that the rate of galaxy building/modifying was much larger fairly recently in the universe. Butcher and Oemler showed that the fraction of blue galaxies in large clusters of galaxies rises dramatically beyond a redshift $z \sim 0.3$. Recent work by Lavery and Henry (1988) (see Fig. 1) shows that these blue galaxies are probably in the throes of star formation caused by close encounters with other galaxies. So a large number of galaxies were still in a state of flux until fairly recently.

3. Models of Galaxy Formation

Given some set of cosmological parameters (e.g. Ω_o, H_o and the shape of the density perturbation spectrum) one can use N-body models to follow the development of galaxy-sized systems of dissipationless (non-baryonic) dark matter. Using density perturbation spectra that are simple power laws in wavenumber,

$$P(k) = Ak^n ,$$

normalised to give the current density of galaxies at $z = 0$, Quinn *et al.* (1986) have shown that the dark matter halos form by a sequence of mergers of smaller protohalo fragments (a similar result has been obtained for CDM by Frenk *et al.* 1985). The formation of an individual halo is shown in Fig. 2. Zurek *et al.* (1988) emphasised the organised nature of this lumpy formation process. They pointed out that a dynamical memory of the initial conditions is carried through to the final virialised halos due to the action of tides and dynamical friction on lumps of protohalo material. This memory implies that power spectra with indices $-3 < n < -1$ are necessary to account for the current flat rotation curves of spiral galaxies. In these situations we expect the evolution to proceed by a sequence of mergers from smaller to larger mass scales since the spectrum of mass fluctuations ($\delta M/M$) implies a collapse time that increases with mass:

$$t_{collapse} \propto M^{\frac{1}{4}(n+3)} .$$

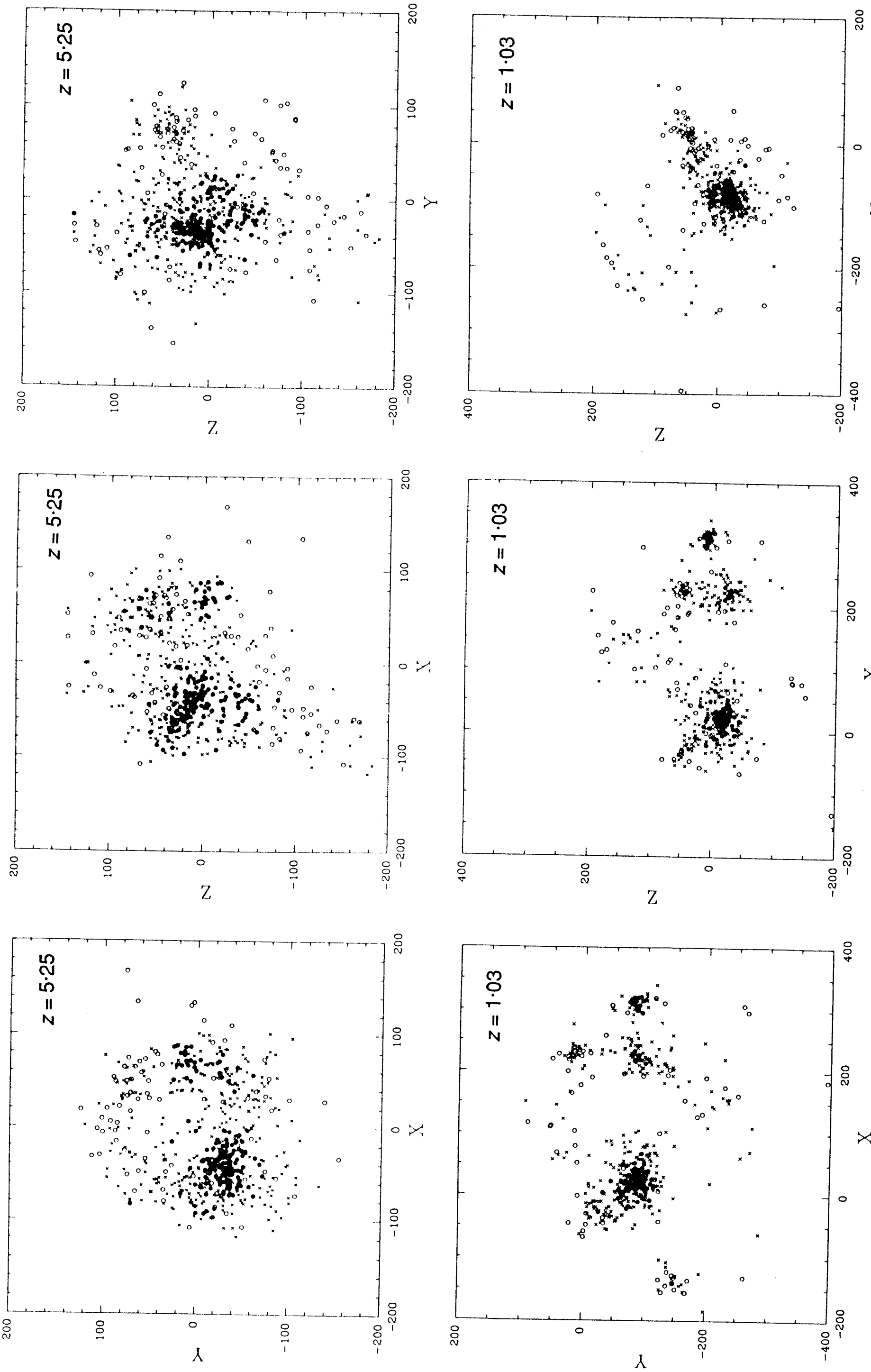
The N-body models show a large increase in the number of halos of a size appropriate to large galaxies forming after a redshift of approximately 4. As a check on this we can compute the expected collapse time for galaxies of a given size. Fall (1990), following on the work of Fall and Efstathiou (1980), proceeded by equating the current specific angular momenta (J/M) of disk galaxies with the angular momentum content of dark halos. The amount of angular momentum present in dark matter halos (as measured in the cosmological N-body experiments) is similar to the currently observed angular momentum content of disks. This would imply that disks collapsed preserving most of the angular momentum they acquired before they underwent dissipative collapse:

$$\left(\frac{J}{M}\right)_{Disk} = \left(\frac{J}{M}\right)_{Halo} .$$

For an exponential disk:

$$M_D = 2\pi\mu_o\alpha^{-2} ,$$

$$J_D = 4\pi\mu_o v_c\alpha^{-3} ,$$


z = 5·25
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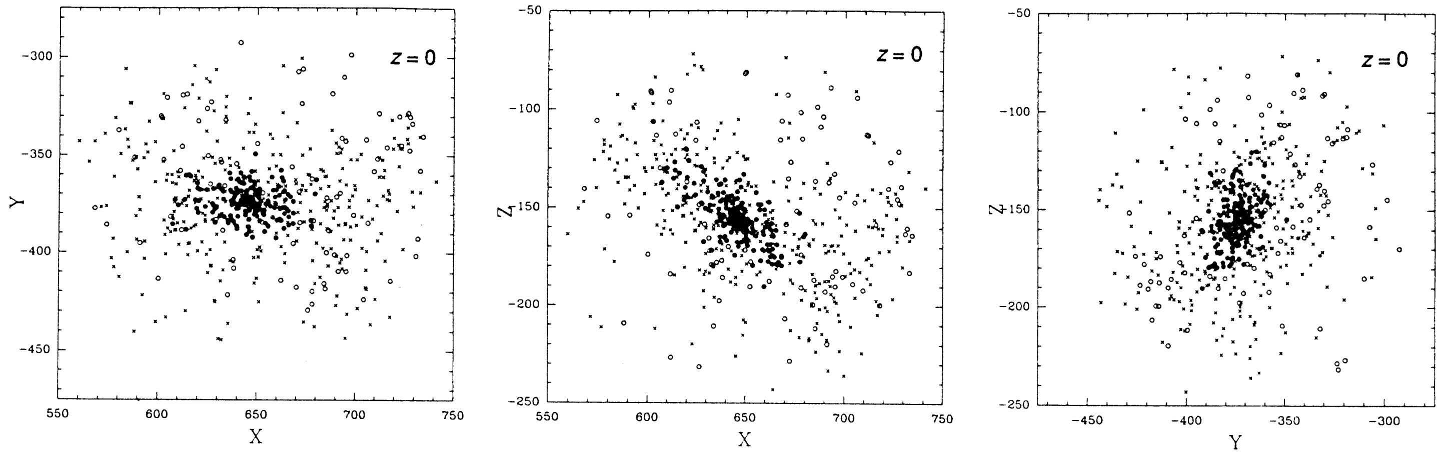

Fig. 2. The evolution of a protohalo from $z = 5.25$ to $z = 0$ for $n = -1$. At $z = 0$ all the bound particles within 100 kpc of the centre were tagged and divided into three bins of binding energy. The most bound particles are marked as solid dots, the least bound as open circles and intermediate energies as a cross. The most bound particles at $z = 0$ occupied the cores of subclumps seen at $z = 1.03$ which merged to form the final halo. At $z = 5.25$, the most bound particles also generally live in regions of excess density. Note that each frame at a given z has the same linear scale in both axes (measured in kpc, non-comoving) and shows three orthogonal cartesian projections.

where the surface density of the disk is

$$\mu = \mu_o e^{-\alpha r}$$

and the disk has a flat rotation curve with an asymptotic circular velocity of v_c. For an isothermal dark matter halo:

$$M_H = v_c{}^2 r G^{-1} ,$$

$$J_H = \sqrt{2}\lambda_H v_c{}^3 r^2 G^{-1} ,$$

where λ_H is Peebles's dimensionless spin parameter for the halo. By forming J/M and equating we obtain

$$\alpha r = \sqrt{2}\lambda_H .$$

The collapse time of a galaxy must be at least twice the free fall time from the outer edge of the system. For an isothermal halo the free fall time is

$$\tau = \left(\frac{\pi}{2}\right)^{\frac{1}{2}} \frac{r}{v_c} .$$

Therefore, we get

$$t_{collapse} > 2\tau = \frac{\sqrt{\pi}}{\alpha v_c \lambda_H} .$$

The relationship between α and v_c can be determined from observations of spirals leading to an estimate of the collapse epoch of

$$1 + z_{collapse} < 3\left(\frac{\lambda_H}{0.06}\right)^{\frac{2}{3}}$$

for $\Omega_o = 1$. Hence it is not surprising that we see a lot of merging in our models between a redshift of 4 and zero and indeed that the most distance objects we have yet observed have redshifts less than 4.

4. New Data from $z > 1$

If galaxies are actually forming at redshifts less than 4 it should in principle be possible to observe them with large ground based telescopes. The trick is to find them initially. Recent work by Chambers *et al.* (1990) has uncovered a successful method of locating high redshift galaxies based on low frequency radio observations. Miley and others noticed that the fraction of radio sources with optical counterparts decreased as the radio spectral index α ($Flux \propto \nu^{-\alpha}$) increased. The suspicion was that many of these steep spectrum sources were high redshift galaxies. After obtaining accurate positions for some of these sources with the VLA, Chambers *et al.* took optical specta and direct images using 4 m class telescopes. What they found were galaxies ranging from $z \sim 2$ to $z \sim 4$. Continuum images showed that the galaxies were extended and lumpy as the *N*-body models would imply. The spectral energy distribution showed a significant red-bump around 8000 Å. If the galaxies were ellipticals (as most of the powerful radio galaxies are at smaller redshifts) then this bump may be associated with a old stellar population. At a redshift of approximately 4, the time since the Big Bang is approximately 10^9 yr for $\Omega = 1$ and $H_0 = 50$. This is comparable with the age of any old stellar population responsible for the red light. Hence if the red emission is starlight then we are faced with an observation that implies stellar systems must have formed at a much higher redshift than 4.

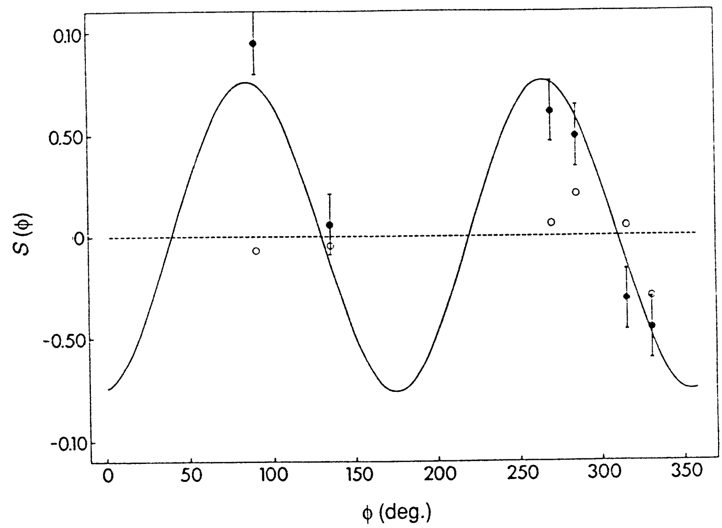

Fig. 3. The fractional polarisation in the V band of 3C368 (solid points) as a function of polarimeter angle. The solid curve shows the expected behaviour of a source with a fixed level of polarisation in a single direction. The open points are measurements of faint stars in the the same field as 3C368.

The central issue in 'observational' galaxy formation has now become the source of the red and blue continuum emission in the Chambers *et al.* galaxies. In one case we do have an indication that not all of the light is coming from stars. The radio source 3C368 ($z = 1.1$) has been observed by di Serego Alighieri *et al.* (1989) using an imaging polarimeter. They detected extended polarisation of the source in the V band at the 8% level (see Fig. 3) and 2% in the R band. The direction of the polarised E vector is within 25° of perpendicular to the extended continuum and radio structures. This suggests that a large fraction of the ultraviolet light in 3C368 does not come directly from stars but rather could be scattered radiation from the active nuclear region. The decline of the polarisation in the red does not preclude the possibility that a large fraction of the total emission comes from an old stellar population. Chambers *et al.* suggested that extranuclear star formation induced by the radio jets may be taking place and it is unclear what the initial mass function of such a stellar population would be. It is clearly imperative to investigate the red emission in these galaxies further in order to set some hard constraints on the epoch of formation of the stellar populations involved. One point to be keep firmly in mind is that the Chambers *et al.* galaxies are exceptional in the sense of being very powerful radio sources. It may well be that they are not representative of the general galaxy population.

5. Conclusions

Many of the 'peculiarities' of nearby galaxies (tidal tails, shells, counter-rotating cores, thick disks, bursts of star formation) have been investigated with numerical models and found to be naturally accounted for by tidal interactions between galaxies. The statistics of these features argue for most massive galaxies having suffered several infall events during the past 5×10^9 yr. The low specific angular momentum content of ellipticals relative to spirals argues that ellipticals were formed from protogalaxies that were very lumpy. Such lumpy protogalaxies are now being observed at redshifts less than 4. So many bright galaxies may well have formed and evolved by the merger of subsystems making galaxy formation from pre-existing systems an ongoing process. The epoch when the protogalactic lumps necessary to form a large galaxy first fell together can be constrained by the collapse time of systems of various sizes. The work of Fall has demonstrated that on very general grounds we would expect most large galaxies to begin their formation at redshifts less than 4. This is in agreement with N-body models of the evolution of power spectra consistent with the current internal structure of halos and the limits of detections of quasar if indeed the QSOs are individual galaxies. The most severe problem for this picture of galaxy formation rests with the discovery of galaxies at redshifts of order 4 that could at that time already have a stellar population that is more than 10^9 yr old. If such a stellar population exists then either the stars were born in much smaller systems at very high redshift or the epoch of large galaxy formation is underestimated by the collapse arguments. It could still be the case that the high redshift galaxies so far detected are exceptional and were formed in a different manner to the majority of normal galaxies.

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