FORMATION AND SECULAR EVOLUTION OF ELLIPTICAL GALAXIES

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ABSTRACT. Three ways have been proposed to make elliptical galaxies: cooling by gas dynamical processes at late epochs, Compton cooling at early times and merging. These theories must address a variety of observational constraints, the most severe being the problems of slow rotation and high central phase densities. I look at some aspects of all three theories with particular attention to key numerical simulations and observations that can distinguish between the scenarios.

1. INTRODUCTION

To my mind, the most unique feature of this conference has been the dazzling array of talks on the secular evolution of elliptical galaxies. There's been nothing like this before. There were at least three talks about galaxy formation (Ivan King sat through all three). Star formation in cooling flows is slowly becoming well-established, though puzzling. Elliptical galaxies are influenced by cannibalism, merging and accretion; the resultant shells are seen for a long time. The centers of galaxies may have their integrals slowly broken by the central massive object leading to stochasticity and feeding.

The bottom line is that I find my charge to review secular evolution puzzling. I thought that I might talk a bit about galaxy formation (the most certain of all secular events) covering a couple of topics that have had little attention at this conference.

Galaxy formation theory has not advanced as briskly as our understanding of their internal structure. Rees (1977) has lamented the hazards of the roads to be traveled and likened the process to searches for probes of the Universe between a redshift of 3.5 (quasars) and 1000 (the microwave background). The one success of the theory has been the calculation of the characteristic masses of galaxies as the scale where dissipation breaks the hierarchy. While this idea has an irresistible appeal, there are problems with the way it has been calculated.

Here, I will examine three scenarios for the formation of elliptical galaxies. These are: 1) late dissipative when a large fraction of the binding energy is radiated by gas cooling 2) early dissipative when Compton cooling off the microwave background is important and 3) merging. I will show that there are key observations that will help discriminate between the three. In keeping with my charge to

T. de Zeeuw (ed.), Structure and Dynamics of Elliptical Galaxies, 331–338.

describe secular evolution, I'll also mention some long lasting dynamical effects that may still be visible.

At this conference, Carlberg has stressed the constraints that the core properties of ellipticals place on their formation. An important part of the discussion will be the ways the three scenarios address this problem and the longer standing problem of slow rotation (cf Illingworth 1977).

2. DISSIPATIONAL GALAXY FORMATION

Normally, it's said that the criterion for gas dynamics to have had significant effect is that the cooling time is less than the dynamical time. Contrary to the usual interpretation, this would seem like a good criterion for gas dynamics to **stop** restructuring galaxies. Once the cooling time is shorter than the dynamical time, the gas should be thermally unstable. The denser regions cool faster, the hot diffuse phase pushes on them and clouds form with large density contrasts and low temperatures. We must then ask if star formation occurs within a collapse time. In short, does the collapse rapidly become dissipationless? Avoiding this may be a strong argument against galaxies cooling too quickly. On the other hand, if they don't cool there won't be any contrast between galaxies and their environment. Galaxies have clearly pinched off the clustering hierarchy and gas dynamics is certainly the cause. Either the gas must follow the ridge line $\tau_{cool} = \tau_{ff}$ as closely as possible or we must find ways to loose energy after the formation of clouds.

Dark matter changes most of the details of galaxy formation in a manner that hasn't been well chronicled in the literature (though see White and Rees 1978). A classic argument by Ostriker and Rees (1977) is that cooling due to bremsstrahlung sets a characteristic scale of $\sim$ 80 kpc. The gas is assumed to be at a virial temp,

$$T_{gas} = 5.2 \times 10^5 K \ \mathbf{M}_{11} \ \mathbf{R}_{10}^{-1}$$

where $\mathbf{R}_{10}$ is the radius in units of 10 kpc and $\mathbf{M}_{11}$ is the total mass in units of $10^{11}\mathrm{M}_\odot$, with a gas density

$$\rho = 1.6 \times 10^{-24} g \ cm^{-3} \ \mathbf{F} \ \mathbf{M}_{11} \ \mathbf{R}_{10}^{-3},$$

where $\mathbf{F}$ is the fraction of the matter that can dissipate. The bremsstrahlung cooling time for this gas is

$$\tau_{brem} = 2.2 \times 10^{14} s \ \mathbf{M}_{11}^{-1/2} \ \mathbf{F}^{-1} \ \mathbf{R}_{10}^{3/2}.$$

By comparison, the free fall time is given by

$$\tau_{ff} = 7.3 \times 10^{14} \ \mathbf{M}_{11}^{-1/2} \ \mathbf{R}_{10}^{3/2}$$

equating τ_{brem} to τ_{ff}, we find a characteristic radius: $R_{cool} = 73$ Fkpc. With $\mathbf{F} =$ 1, the radius 73 kpc rings true as the radius that galaxies collapse from, but when we take the currently popular figure (Faber 1983, Gunn 1983) $\mathbf{F} = 0.07$ for the ratio of light to dark matter, the radius 5 kpc rings equally true for the final radius of collapse where dissipation **stops** being important.

Of course, at the virial temperatures of galaxies, cooling by radiative recombination dominates over bremsstrahlung. While in principle, this should lead to horrid complications, over the range of $T = 10^4\text{-}10^6$, the value of the cooling constant Λ for a zero-metal gas is nearly constant at a value of 2×10^{-23}, so that

$$\tau_{rad} = 5.5 \times 10^{13} s \ \mathbf{R}_{10}^2 \ \mathbf{F}^{-1}.$$

For a value of $\mathbf{F}$ equal to .07, we find that thermal instabilities should occur at a radius of 10 kpc.

The properties of the clouds that form are easily estimated if the clouds are in pressure balance. The hot medium will be nearly fully ionized and have a temperature of $1\text{-}2 \times 10^6$ K, while the clouds will rapidly cool to approximately 10^4 K. The ratio of the densities $\mathbf{f} = \rho_{cool}/\rho_{hot}$ is just $2 \times T_{hot}/T_{cool}$. These clouds have several attractive properties. First, since we assumed that the protogalaxy is collapsing nearly quasistatically until it becomes thermal unstable, this means that we have one Jeans mass in one Jeans length. The Jeans mass in the clouds will be roughly $(T_{cool}/T_{hot})^2 \ \mathbf{F} \ \mathbf{M}_{11}$ or $10^{-5} \ \mathbf{F}^{-1} \ \mathbf{M}_{11}$. Fall and Rees (1985) associate this mass with that of the globular clusters. While it is high for a globular cluster, they point out that there will be mass loss. I regret that I had not seen their paper at the time of the Princeton meeting. They argue that various other physical processes favor clouds of this size. I have a simpler argument that shows that clouds this size form. Since a large fraction of the gas will be tied up in the clouds, their filling factor will be roughly $\mathbf{f}$, previously defined as the ratio of the densities. For illustrative purposes, let's consider N clouds of fixed size. The mean free path of the clouds is $N^{1/3} \ \mathbf{f}^{-2/3}$ times the radius of the protogalaxy. Clouds collide in a dynamical time if there are more than $\sim 10^5$ of them. If there are less than this number, they are gravitationally unstable and form something, presumably star clusters. If there are more, then when the clouds collide, the shock will be isothermal and lead to a large density increase in the postshock gas. For a shock velocity of 300 km s^{-1}, the densities rise by over two orders of magnitude and the Jean's mass decreases by an order of magnitude. So if there are $\sim 10^6$ of them, they collide in a dynamical time and immediately become Jean's unstable. If there are still more, they coagulate on a time scale that's short compared to a dynamical time and eventually reach the Jean's threshold in a few dynamical times.

Will these clouds with densities contrasts of 200-400 at a radius of 10 kpc evolve to form an elliptical galaxy with a radius of 3 kpc and a dense core? Well, maybe. Each time that the clouds collide, they can only reduce their relative kinetic energy. If they have to radiate enough to collapse by a factor of three, it takes about 15 collisions (Carlberg, Lake and Norman 1986). If the clouds start with masses of $\sim 10^3 M_\odot$, then it looks like this could work. But, there's some three card Monty going on here. A $\mathbf{F}$ of 0.07 is small for a scale of 10 kpc. Let's suppose that the dark matter in ellipticals has the same distribution that we see in spiral galaxies. Then at these radii, a more appropriate value would be 0.5. If ellipticals are surrounded by halos with the run of densities seen in spiral galaxies, they become thermally unstable at a radius of roughly 40-50 kpc. Without any halo, the collapsing cloud becomes thermally unstable at a radius approaching a Mpc. At either of these radii, a diffuse iceberg forms rather than an elliptical galaxy unless the clouds suffer many collisions.

It's easy enough to scheme up a way for the clouds to keep dissipating. They start small, bust up, reform, etc. until they've radiated away a lot of energy. It may happen that way. It stops looking very natural. We may just have to accept that all these collisions do occur. The good news is that there is a lot of action with clouds busting up and reforming during galaxy formation. It's a good epoch for hungry monsters. Star formation is occuring quickly, which bodes well for searches for primeval galaxies. The best news is that the physics of dissipational collapse is easy to simulate. The energy is being radiated by cloud-cloud collisions with mean free paths that are $\mathbf{O}(10^{-1})$ the size of the system. This is exactly the circumstance that Carlberg and I are now simulating using the San Diego Supercomputers (cf. Carlberg, Lake and Norman 1986). I now think that there is little reason to be apologetic about our dissipation scheme of bouncing particles with a coefficient of restitution. This captures the essential physics and means that we will learn a lot from these simulations. So far, we've learned a lot about the angular momentum problem. We find that when we collapse warm perturbations (velocity dispersion 30% of the virial value); the gas settles gently into a disk. If we collapse cold perturbations ($\sigma < 0.2$), there is a lot of angular momentum transfer and a dense, slowly rotating elliptical galaxy forms. The collapse of clouds is a good way to make all kinds of galaxies.

Before leaving this section, let's take a last look at the protoglobular clusters. If you accept the universal ratio of light to dark mass, you find that the Jean's mass of the clouds at the time of thermal instability is dependent on a a fairly high power of the mass of the protogalaxy. This deserves attention to see if it's really a viable theory for the origin of globulars.

3. BUT ELLIPTICALS ARE COMPTON COOLED

The previous section considered only the role of radiative cooling. In the early Universe, there is another mechanism– Compton cooling (cf. Ostriker and Rees 1977). This cooling owes to the scattering of the microwave (then infrared) background photons off electrons, robbing the latter of energy. It is independent of density, **F** and temperature (as long as $T_{electron} >> T_{radiation}$). The Compton cooling timescale for a completely ionized gas is given by

$$\tau_{comp} = 3.8 \times 10^{19}(1+z)^{-4}s,$$

where z is the redshift. As perturbations evolve in the Universe, they experience turnaround when their mean density is 5.5 times the cosmological density. The two times τ_{comp} and τ_{ff} are equal for perturbations that are turning around at a z of 10. At this redshift, both times are 5.5×10^{15} s. By comparison, T_{rad} is $8.8 \times 10^{14}\ \mathbf{M}_{11}^{2/3}\ \mathbf{F}^{-1}$ s.

If Comptonization is the only cooling mechanism, there isn't any thermal instability. Dense regions don't cool faster. Jeans and shape stabilities may still be important. It's important to know when Compton cooling dominates over radiative cooling. For an object just turning around, this occurs when $(1+z) = 25(\mathbf{F}\ \mathbf{M}_{11})^{-1/2}$ If **F** is 1, this yields the surprising result that Compton cooling isn't dominant until a redshift of 25 rather than 10.

What is **F** for perturbations turning around at redshifts of 10-20? We can gain some insight from the central densities of halos of spiral galaxies. From the data and analysis for NGC3198 (van Albada *et al.* 1985), we find a core halo density of $3.5 \times 10^{-25}\ g\ cm^{-3}$. This density sets an upper limit to the turnaround redshift of roughly 10. We find similar values for the sample of Carrignan and Freeman

(Carrignan 1983, Carrignan and Freeman 1985). It would seem that dark matter can't participate in galaxy formation before a redshift of ~ 10. So **F** is probably **O**(1) at redshifts of order 20.

Even if thermal instabilities don't exist, the efficiency of Compton cooling leads to shape instability. The shocking pancake will produce stars *but very little of the binding energy of the galaxy is radiated.* If the protogalaxy pancakes at a time when its binding energy is appropriate for an elliptical galaxy. The high phase densities in the resultant sheet of stars is ideal for making the cores. The most likely time that such a sheet formed is at a redshift of 20. At this time, Compton cooling keeps the collapsing cloud at low temperatures and there are barely thermal instabilities.

The best argument that I can think of for galaxy formation in the Compton cooled era is that it affords the best chance of hiding baryons. There are several important "estimates" of Ω, the ratio of the mean mass density of the universe to the critical density. Ω_{stars} is about 5×10^{-3}. $\Omega_{baryons}$ determined from calculations of nucleosynthesis is roughly 0.1 (Olive *et. al.* 1981). Cosmic virial theorems yield $\Omega_{cvt} = 0.1$. Finally, the New Religion (or New Inflation) says that $\Omega_{true} = 1$. In the preceding list, science is accurate to a factor of two, while religion is exact. Even with these uncertainties, there are two discrepancies, one between stars and baryons and the other between religion and the universe. Its important to simulate the compton cooled era to see if elliptical galaxy formation can work in detail and if there is some way to hide baryons. An example of the interesting physical questions that await analysis is the importance of compton drag in slowing rotation and preventing fragmentation.

4. MERGERS

I'm amazed at how little discussion there has been of the merger hypothesis at this meeting. The two most difficult hurdles for the merger hypothesis are the L-σ relation (cf. Ostriker 1980, Tremaine 1981) and the extremely high central phase densities of ellipticals (Carlberg, this conference).

Recently, Dressler and I (1986) measured the velocity dispersion of objects from the Arp (1966) and the Arp-Madore (1986) Atlases that have characteristics of recently merged galaxies. Accurate velocity dispersions of objects dominated by Balmer lines in the blue were measured using the uncontaminated Ca triplet feature in the extreme red (8400-8700 Å).

What did we expect? Most mergers will occur when a pair of galaxies is just bound (White 1979). This is easy to see as the phase space of bound orbits is largest at marginal binding. Galaxies that are just unbound may merge if the orbital parameters are just right; they become bound by ejecting a fraction of their mass with positive energy. We consider the merger of spirals, since we selected galaxies with streamers or tails — clear indications of an initially cold component. Roughly half of our selected sample shows signs of star formation; the initial systems must have had a considerable gas content.

For mergers at zero orbital energy, the binding energy of the remnant is the sum of the binding energies of the initial spirals. The luminosity in the H-band of the remnant will be the sum of the luminosities in the H-band of the original spirals. Our last assumption is that the merging spirals have the same H-luminosity. This biases our result toward high luminosities at a fixed dispersion velocity, but the bias is small. We can now take the H-band Fisher-Tully relation for spirals and construct a model Faber-Jackson relation for ellipticals.

Aaronson, Huchra and Mould (1980) give a Fisher-Tully relation using aperture magnitudes of:

$$H^{abs}_{-0.5} = -21.23 - 10[\log \Delta V_{20} - 2.5].$$

Using their growth curves, we find a mean correction of 0.5 magnitudes for total magnitudes yielding

$$H^{abs}_{spirals} = -21.7 - 10[\log \Delta V_{20} - 2.5].$$

The quantity ΔV_{20} is twice the circular velocity in the disk which is in turn $\sqrt{2}\sigma$, where σ is the velocity dispersion. Using these transformations and our luminosity and binding energy sum rules, we expect

$$H^{abs}_{hypoth.merger} = -24.9 - 10[\log(\sigma) - 2.3].$$

We compare this to the Faber-Jackson (1976) relation for ellipticals (de Vaucouleurs and Olson 1982, with a mean B-H = 4):

$$H^{abs}_{E} = -23.4 - 10(\log(\sigma) - 2.3).$$

Our expectation is that there will be a 1.5 magnitude difference between merger remnants and normal ellipticals. Given the steepness of luminosity-velocity dispersion relation, this means that the velocity dispersions of merger remnants should be 30% lower than that observed in elliptical galaxies. Similar conclusions were reached by Veeraraghavan and White (1984) employing blue magnitudes and fading the disk and bulge separately.

What did we find? Our sample of merger remnants had a $\sigma(M_B = -21)$ of 184 km s^{-1} as compared to 184 for Sargent *et al.* (1977), 237 for Faber and Jackson (1976), 201 for Schechter and Gunn (1979), 237 for Whitmore *et al.* (1979) and 220 for Terlevich *et al.* (1981). The merger remnants are on the low side, but not outside the range seen in samples of elliptical galaxies.

We used blue luminosities. Many of the galaxies had bluer colors than normal ellipticals. If we fade the blue galaxies using starburst models (an extreme case, Larson and Tinsley 1978), the resultant $\sigma(M_B = -21)$ is 193 km s^{-1}.

Two of the three galaxies with blue colors (Arp 224 and Arp 226) were on Toomre's (1977) list of "prospects for ongoing mergers". A better observation technique for these and some other candidates (notably NGC 3256 and Arp 243) would be to use H-magnitudes which are much less sensitive to the recent bursts of star formation. An ideal follow-up to our study is one using measurements of the velocity dispersion from the Calcium triplet together with H-band luminosities.

The second problem of large core densities is unsettled. The bulges of spiral galaxies have even large phase densities than ellipticals. Carlberg pointed out a galaxy that had too small a core radius (large phase density) and associated it with a merger event. In using central phase densities to constrain galaxy formation scenarios, we assume that the cores are formed with the rest of the galaxy. If instead, they are secondary, formed by subsequent gas infall then their formation is decompiled from initial conditions. Space Telescope can make some key observations here. First, it can image merger remnants in the I-band in the same way that Kormendy (1985) has resolved the cores of nearby ellipticals. This way, we'll know *empirically* if phase space densities are a problem for the merger hypothesis. Also, if the cores of ellipticals (and/or merger remnants) are made by secondary infall, ST data will show that they rotate rapidly. I would have bet against this before I saw Kormendy's spectacular data (this conference) on the core of M31. That core certainly evolved after the galaxy formed.

Finally we may get a better understanding of all these issues using numerical simulation. There's no reason not to simulate the merger of two galaxies each with 100,000 particles. We can follow the dissipational collapse of galaxies. Simulations of collapsing Compton cooled clouds are interesting for both galaxy formation and for pointers to the mystery of Pop III and the missing baryons.

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DISCUSSION

Fall: Martin Rees and I studied many of the processes you discussed. Our main point was that a collapsing proto–galaxy would be thermally unstable and would develop a two–phase structure: cold clouds at $T \sim 10^4 K$ compressed by the surrounding hot gas at $T \sim 10^6 K$. The clouds with masses exceeding some critical value of order $10^6 M_\odot$ would then be gravitationally unstable; we identified these objects as the progenitors of globular clusters. In contrast to your claim, the clouds must cool slowly at temperatures just below $10^4 K$ to imprint a characteristic mass of order $10^6 M_\odot$. The condition for this to happen is that the sound crossing times of the clouds be *shorter* than their cooling times. A complete account of our work was published last year (1985, *Astroph. J.*, **298**, 18).