MERGERS IN THE LOCAL UNIVERSE

MERGERS AND THE FORMATION OF MASSIVE ELLIPTICALS

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1. Introduction and Abstract

Many nearby luminous elliptical galaxies exhibit counter-rotating cores, minor axis rotation or peculiar velocity fields. These phenomena require that merging and accretion events played a major role in the formation of ellipticals and, equally important, that stars dominated significantly over gas in the merger progenitors. Low redshift analogues to the last stages in the formation of massive ellipticals can be observed in ultraluminous IRAS mergers. However, this does not imply that ellipticals generally formed in spiral-spiral mergers. Mergers can also occur as a consequence of inhomogenous collapse or hierarchical bottom-up structure formation and it is actually more likely that the progenitors of present-day ellipticals did not resemble present-day spirals.

Although *some* ellipticals most certainly were and still are formed at low redshift, the *general* formation epoch of massive ellipticals is likely to be found at redshifts > 1. The evidence for this is threefold: (a) the homogenous stellar populations of ellipticals, most notably the tight correlation between colors/absorption linestrengths and velocity dispersion, (b) the high overabundance of light elements relative to iron and (c) the very weak evolution of colors and linestrengths of ellipticals with redshift.

2. Peculiar cores in ellipticals

Peculiar cores in ellipticals are characterized by angular momentum vectors opposite or perpendicular to those of the main bodies of the galaxies. It is evident that this kind of structure could not have been formed if the galaxy had been assembled from mainly gaseous constituents because efficient angular momentum exchange would have lined up the angular momentum vectors of inner and outer parts. In other words, the merging constituents

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did already consist, to at least a significant fraction, of stars. Despite of kinematic decoupling, peculiar cores are in general stable, long-lived phenomena and so, unlike shells and ripples in the outer parts of galaxies, represent a long-term memory of the formation history of an object.

About 1/3 of nearby *luminous* ellipticals show peculiar core kinematics (Bender 1990). This fraction is, e.g., also found in the Virgo cluster: of the nine brightest Virgo ellipticals ($M_B < -20.5$, $\mathrm{H}_o = 50\,\mathrm{km/s/Mpc}$) three show kinematically decoupled cores (NGC 4365, 4406, 4472). Because of projection statistics it then follows that **more than 50% of all luminous ellipticals contain kinematically decoupled cores**. In most of them, the analysis of the line-of-sight velocity distributions shows that the peculiar cores are likely to be rapidly spinning thick disks or torus-like components (Franx and Illingworth 1988, Bender 1988, 1990, Rix and White 1992, Surma and Bender 1995). They formed dissipatively and must have involved substantial star formation (because of high v/σ and metallicities higher than in the main bodies), see Bender and Surma (1992), Davies et al. (1993), Surma and Bender (1995). These components have masses in the range $10^9...10^{10}\,\mathrm{M}_\odot$ and radii of up to about one kiloparsec.

Most of the ellipticals with peculiar cores belong to the class of boxy ellipticals or ellipticals with irregular isophotes. There is only one elliptical known so far (NGC 1700, Franx et al. 1989) which has a counter-rotating core and *significantly disky* isophotes. Boxy ellipticals are in general more luminous than disky ellipticals (e.g., Bender et al. 1993b). Therefore the natural interpretation of these findings is that mergers that lead to counter-rotating peculiar cores will usually form luminous, mainly boxy, ellipticals. Of course, it is to be expected that pre-existing disks cannot survive major mergers (e.g. Quinn, Hernquist and Fullagar 1993) and, indeed, recent simulations by Steinmetz (1995) also show that dissipationless merging produces preferentially boxy isophotes outside the core. Consequently, the observed correlation between peculiar cores and boxy isophotes of the main bodies is very plausible.

A note of caution: The peculiar core kinematics in some ellipticals can possibly be explained in ways different from the above scenario. E.g., the decoupled core could be due to streaming in a triaxial figure, obliquely projected (Binney 1985, Franx et al. 1991, Statler 1994), or due to *dissipationless* merging with a small compact elliptical or a bulge dominated S0 (Kormendy 1984, Balcells and Quinn 1990). It seems clear however that these latter scenarios cannot account for the formation of the majority of ellipticals with peculiar cores. The reasons are that rotation amplitudes in the cores are in general too high and that core metallicities are enhanced with respect to the main body (Bender and Surma 1992). Similarly unlikely is the accretion of gas-rich irregulars because they simply do not contain enough gas to form a massive central component. Typically, a much larger amount of gas is needed, like the one found in massive spirals.

Finally, it is also noteworthy that ellipticals with peculiar cores are found in all environments, in rich clusters as well as in small groups; examples for the latter are NGC 5322 (Bender 1988), IC 1459 (Franx and Illingworth 1988), or NGC 3608 (Jedrzejewski and Schechter 1988).

3. The analogy between IRAS mergers and the formation of massive elliptical galaxies

A plausible formation scenario for ellipticals with kinematically decoupled cores can be sketched by inspecting the properties of ultraluminous IRAS galaxies and by N-body simulations of merging spirals.

Hernquist and Barnes (1991), Barnes and Hernquist (1996), and Barnes, this conference showed in their simulations that ellipticals with counter-rotating cores can originate in spiral-spiral mergers. The model spirals consisted of dark matter, stars and gas in the usual mix. While the stars undergo a process of violent relaxation during merging and form a smooth $r^{1/4}$ main body, the cold gas is efficiently transported to the center of the merger where it settles into a rapidly rotating thick disk or torus. This result of the merger simulations is consistent with the observations of the molecular gas distributions in IRAS mergers, e.g. NGC 520, Arp 220 or NGC 7252 (e.g. Sanders et al. 1988, 1991; Schweizer 1990; Kormendy and Sanders 1992). Both simulations and observations show that the molecular gas tori can be kinematically decoupled from the main bodies of the galaxies, i.e. their angular momentum vectors can be opposite or perpendicular to the ones of the main bodies. The molecular gas masses observed in the centers of luminous IRAS mergers are very similar to those of the counter-rotating cores ($10^9 - 10^{10}\,\mathrm{M}_\odot$, Sanders et al. 1991); the same is true with respect to the radii which are typically of the order of a few hundred parsecs or smaller.

The high concentration of molecular gas in the center of the merger leads to violent star formation and forms a rotationally flattened central stellar component. This component is likely to be very metal-rich because the molecular clouds were pre-enriched and also because the IMF may be top-heavy in mergers (e.g., Wright et al. 1988, Bernlöhr 1993). In some of the IRAS mergers we can observe this process just now (e.g. NGC 520, Arp 220). Once the IRAS mergers have aged by about 5 Gyrs, the relics of the central starbursts are likely to resemble the decoupled cores observed in ellipticals today, both with respect to kinematics and metallicity (Bender and Surma 1992). In some mergers, newly formed stars may not only be found in the center but also at larger radii. These stars are due to star formation triggered in the early phases of the merging (Fritze-von-Alvensleben and Gerhard 1994) and may contribute to a smooth overall appearance of the line-strengths gradients after several Gigayears.

These considerations show that a *qualitative* understanding of the formation of ellipticals via *dissipative merging* can be reached in consistency with observations of present day mergers and N-body simulations. However, the plausible analogy between IRAS mergers and the formation of ellipticals does of course neither imply that ellipticals must have formed via merging of spirals nor that they formed late (i.e. at low z) in general. It is equally possible that *both* ellipticals and spheroids formed at higher redshifts by (hierarchical) processes involving *both* merging-induced violent relaxation and dissipation. The relative amount of dissipation varied as a function of luminosity and other protogalactic parameters (like density and environment) and determined the degree of anisotropy of the final object. More luminous ellipticals may on average have assembled from more evolved progenitors (in which most of the baryonic matter had already been transformed into stars) and, thus, not only velocity anisotropy but also kinematic de-coupling between core and main body may have been produced in these objects. The important parameter determining whether the final object would show peculiar kinematics and features in the line-strength gradients is the *ratio between star formation timescale and the timescale over which violent mergings occured.* For a more detailed discussion of these points see Bender and Surma (1992), Bender, Burstein and Faber (1992, 1994).

As the discussion of the next paragraphs will show, it is indeed indicated that most luminous ellipticals formed the bulk of their stars at relatively high redshifts and on rather short time scales.

4. The mean ages and star formation histories of massive elliptical galaxies

Despite the large variety of structural properties, the stellar populations of elliptical galaxies are to first order surprisingly homogenous. Colors and line-strengths are one-to-one correlated to such an extent that it makes sense to discuss their stellar populations in wholistic terms (e.g. Sandage and Visvanathan 1978, Burstein et al. 1988; Peletier 1989; Faber et al. 1992). The stellar populations of elliptical galaxies are very tightly related to their central velocity dispersions (σ) (e.g., Dressler et al. 1987, Bender, Burstein and Faber 1993a). It is important to note that there is no difference between ellipticals that appear to have 'normal' kinematics and ellipticals with kinematically decoupled cores.

From existing stellar population synthesis models (e.g., O'Connell 1986;

Bruzual and Charlot 1993; Worthey 1994) one can estimate the combined scatter in age and metallicity from the observed scatter in the Mg$-\sigma$ relation. Bender, Burstein and Faber (1993) found for *luminous ellipticals* that the scatter in age and/or metallicity at a fixed σ must be smaller than 15%. This implies that, **for a given σ, luminous ellipticals cannot have formed continuosly over the Hubble time** (this is consistent with a recent analysis of Schweizer and Seitzer 1992).[1]

Similar constraints on the range of age and/or metallicity at a fixed σ were reached independently for Coma and Virgo cluster luminous ellipticals by Ellis and collaborators (e.g., Ellis 1992) on the basis of the (V-K)$-\sigma$ correlation, and by Renzini and Ciotti (1993) and Ciotti et al. (this conference) on the basis of the small scatter in M/L perpendicular to the fundamental plane.

Further and independent information about the star formation history of ellipticals can be derived from their element abundance ratios. For *luminous* ellipticals, Peletier (1989), Faber et al. (1992) and Davies et al. (1993) found that Mg is overabundant relative to Fe[2]. Over a larger luminosity range, [Mg/Fe] seems to be correlated with velocity dispersion: faint ellipticals have [Mg/Fe]≈ 0 while luminous ellipticals reach [Mg/Fe]≈ 0.4 (Gonzalez 1993, Fisher, Franx and Illingworth 1995). Furthermore, Paquet (1994) could show that, in luminous ellipticals, other light elements like Na and CN are overabundant relative to Fe as well. Evidently, the enrichment of *massive* (high velocity dispersion) ellipticals was in general dominated by Supernovae II, as these are the only significant source of light elements. Supernovae Ia, for comparison, only provide iron peak elements, e.g., Truran and Thielemann (1986). Consequently, the enrichment history of luminous ellipticals differed significantly from the one of the Solar Neighborhood, see Faber et al. (1992), Matteucci and Greggio (1986), Truran and Burkert (1995).

Ellipticals with peculiar cores show the same overabundance in light elements as luminous ellipticals on average. Within the galaxies, the [Mg/Fe] overabundance is in general radially constant up to at least their effective radii (Davies, Sadler and Peletier 1993, Surma and Bender 1995, Paquet 1994). So far, we found in a sample of five peculiar core ellipticals only one object which had solar element ratios in the core and outer parts (NGC

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[1] Low luminosity ellipticals show larger scatter around the mean Mg$-\sigma$ relation and therefore may have a larger age spread. In fact, Gonzalez (1993) showed that low-luminosity Es ($M_T \approx -18$) seem to be systematically younger than giant Es ($M_T \approx -21$), see Faber et al. (1995) and Worthey, this conference. Note that this trend runs opposite to the one expected in a cold-dark-matter model (Kauffman et al. 1993).

[2] This relies mostly on measurements inside the half-light radius of the galaxies.

5322). Again, it is indicated that there is no distiction between 'normal' luminous ellipticals and ellipticals with kinematically decoupled cores.

The prevalence of Supernovae II and in turn the light element overabundance in massive ellipticals can be due to the following effects: (a) a star formation time scale smaller than 10^9 years (SNI explode in significant numbers only after about 1 Gyr after star formation started, e.g. Truran and Burkert 1995), (b) a top heavy initial mass function, (c) a reduced frequency of binary stars (leading to fewer SNI events), (d) selective mass loss mechanisms that resulted in a more efficient loss of SNI elements. Option (c) and (d) are rather unlikely because one expects the binary frequency to be determined by the local process of star formation rather than by global galaxy properties and because selective mass loss processes are likely to work, if at all, only in low mass galaxies (see Gilmore and Wyse 1991). However, also option (b) does not work well, if the overabundance in ellipticals approaches [Mg/Fe]$\approx$ 0.4 dex. Both from the abundance analysis of SNII events as from the abundance pattern of Galactic halo stars (e.g. Fuhrmann, Axer and Gehren 1995), it is very likely that the [Mg/Fe] overabundance is produced by SNII alone without any significant input of Fe from SNI. Turning the argument around, this means that in most luminous ellipticals ([Mg/Fe]$\approx$ 0.3) one can allow for a only rather modest enrichment by SNIa events. The consequence is that **star formation time scales for the bulk of the stars in luminous ellipticals most likely were shorter than roughly 2Gyr**. A moderately top-heavy IMF and *significant* star formation extending over more than 2Gyr are unlikely to solve the overabundance problem because after 2Gyr the Fe enrichment via SNI would start to reduce [Mg/Fe] below the observed value. Note that these considerations do not only apply to the cores of ellipticals but for the bulk of their stars, since the [Mg/Fe] overabundane is similar at all radii (see above).

An important further conclusion can be drawn from these findings: since most present day spirals have gas-to-star ratios smaller than 0.2 and most stars show solar element ratios, **merging of objects similar to present-day spirals cannot produce objects similar to most present-day ellipticals.** However, some ellipticals (e.g. NGC 5322) have [Mg/Fe]$\approx$ 0 and could be late merger products.

5. Ages of ellipticals from their color and line-strength evolution with redshift

In order to constrain formation ages of ellipticals, Aragon-Salamanca et al. (1993) investigated the evolution of V-K colors of Brightest Cluster Members (BCM) up to $z = 0.9$. From the rather small color evolution they concluded that ellipticals have mostly formed at $z > 5$. Although selection effects and the strong dependence of colors on metallicity are major caveats in this analysis, the small color evolution is indeed an important indication for high ages of the bulk of the stars in luminous ellipticals.

Relatively high redshifts of formation are also indicated by the very small and almost non-measurable redshift evolution of the bright end of the galaxy luminosity function (Lilly, this conference), by the Tolman-test (Dickinson, this conference), and by the evolution of the mass-to-light ratios of ellipticals with redshift (Franx, this conference).

Yet another method to constrain the formation ages of ellipticals can be based on the evolution of the Mg$-\sigma$ relation with redshift (Bender, Ziegler and Bruzual 1996, Ziegler and Bender, this conference). Relative to the latter three methods, which measure luminosity evolution and depend on the slope of stellar initial mass function, the Mg$-\sigma$ method is virtually independent from the IMF and, in addition, relatively insensitive to selection effects. This method is likely to represent the least ambiguous test of the redshift evolution of elliptical galaxies.

Bender, Ziegler and Bruzual (1996) have measured the Mg$-\sigma$ relation for a sample of brightest cluster ellipticals at redshifts around 0.4 (see also the poster paper to this conference by Ziegler and Bender). There is clear evidence for the evolution of the stellar populations in ellipticals with redshift. At any given velocity dispersion, the strongest Mg absorption found at $z = 0.4$ is significantly weaker than at $z = 0$, typically by about $\Delta \mathrm{Mg_b} \approx 0.4$ Å. Translating this difference into relative age differences using Worthey's (1994) models implies that the bulk of the stars in luminous ellipticals has indeed formed at $z > 2$ (note that this does *not* exclude mergers with *minor* star formation to happen at lower redshift).

This result is roughly consistent with the predicted mean ages of elliptical galaxies in a cold dark matter universe (Kauffmann 1995). However, the number of data points is still too small to allow a discrimation between the standard ($\Omega = 1$) cold dark matter model and a low density CDM model.

6. Conclusions

Most of the arguments given in the previous sections are still rather qualitative. Nevertheless, the following conclusions can be reached with reasonable confidence:

- Elliptical Galaxies formed from merging of massive progenitor objects that consisted partly of stars and partly of gas.
- The bulk of the stars in the majority of massive cluster ellipticals formed at redshifts above two.

- The star formation time scale for the bulk of the stars in massive ellipticals was most likely shorter than about two Gigayears.
- The high [Mg/Fe] overabundance of massive ellipticals excludes that they have formed from objects similar to present-day spirals.

These conclusions do not contradict the hypothesis that present-day dissipative mergers can form ellipticals. However, these late ellipticals are but a minority among the overall population of ellipticals. The above conclusions neither rule out the possibility of *minor* accretion or merging events taking plaece and leading to the E+A phenomenon. However, these minor events are unlikely to add a large fraction of mass to the already existing underlying old stellar population in ellipticals.

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DISCUSSION:

Dickinson: A Tolman-type analysis of ellipticals in clusters at $z \approx 0.4$ suggests somewhat less B-band luminosity evolution than you measure with the Mg$-\sigma$ relation. Do you know that the galaxies you observed at $z \approx 0.4$ are bona fide ellipticals?

Bender: Most of the objects we observed are in Abell 370 and have HST morphologies. For the other clusters we are currently taking HST images. However, I believe this does not matter very much, because at any given velocity dispersion, even the strongest lined ellipticals at $z \approx 0.4$ have weaker Mg absorption than present day ellipticals. Also note that the evolution as measured by a Tolman-type analysis is IMF dependent while the evolution as derived from Mg$-\sigma$ is not (see Section 5).

Djorgovski: Is there any systematic difference between field and cluster ellipticals in the Mg vs. Fe diagram?

Bender: Frankly, I do not know. But I guess, the effect cannot be very large, because otherwise it would be noticable in the Mg$-\sigma$ and/or Fe$-\sigma$ relation which have been checked for environmental dependencies.

Fritze-von Alvensleben: Damped Lyα systems at $z = 2...4$ contain 10^11 $M_\odot$ of gas, i.e., they contain already the mass of stars + gas in present day spirals. So, early mergers of massive spirals are possible, they will be accompanied by very strong starbursts and could from ellipticals.

Bender: No doubt. But if these early spirals are similar to present-day spirals in gas-to-star ratio and abundance pattern (i.e. [Mg/Fe]$\approx$ 0), then they cannot be the progenitors of most luminous ellipticals (because these have [Mg/Fe]$\approx$ 0.4). On the other hand, if you allow them to contain a much higher gas fraction than 0.2, then of course, it may work out. But in this case, I would not call these high z objects genuine spirals.

Fritze-von Alvensleben: The increase in [Mg/Fe] in a starburst is a direct function of the burst strength. For strong bursts in gas-rich spirals the models I calculated with Ortwin Gerhard seem to indicate that it should well be possible to reach [Mg/Fe] up to 0.5.

Bender: I agree. But you will reach [Mg/Fe] of 0.5 only in the newly formed stars. Outside the core of the merger remnant these will constitute only a small fraction of the total stellar mass and, therefore, after a few Gigayears, the spectrum of the remnant's main body will not show a very high [Mg/Fe] anymore.