Elliptical Galaxies: Detailed Structure, Scaling Relations and Formation

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Abstract. The last decade of research on elliptical galaxies has produced a wealth of new information concerning both their detailed structure and their global scaling relations. We review the old and new results about isophote shapes and subcomponents (Sect. 1.), scaling relations of global parameters and redshift evolution (Sect. 2.), and the ages, metallicities (Sect. 3.) and abundance ratios (Sect. 4.). Finally, we confront the observations with hierarchical formation scenarios of elliptical galaxies (Sect. 5.).

The picture emerging from this variety of observational evidence is broadly consistent with the merging scenario of hierarchical structure formation models, but the stellar population properties of ellipticals pose some challanges. The formation of ellipticals must have always involved some dissipation. The gas fraction at the last major merger event presumably has strong influence on their present day properties. Most elliptical galaxies are old systems, but disky ellipticals might be younger than boxy objects and have more extended star formation histories. The small scatter and the redshift variations of the scaling relation are compatible with passive evolution. The high Mg/Fe overabundances of luminous (boxy) ellipticas point to a rapid star formation episode, while low-luminosity objects have values of Mg/Fe nearly solar, allowing for an extended star formation history.

1. Isophote shapes, sub-components and kinematics

Isophote shapes have proven to be an easily measurable indicator for the internal kinematics and core structure of ellipticals as well as for their radio and X-ray properties (e.g., Bender 1988a, 1997, Bender et al. 1989, Faber et al. 1997, Beuing et al. 1998). Boxy ellipticals are characterized by anisotropy and shallow cores, and by stronger than average radio and X-ray emission. Disky ellipticals contain faint stellar disks, are rotationally flattened, have power-law inner density profiles and show little or no radio and X-ray emission.

The disk-to-bulge ratios of disky ellipticals can be as high as 0.3 and overlap those of S0-galaxies (Rix & White 1990, Scorza & Bender 1995). Generally, the spheroids are rotationally supported and the angular momenta of disks and bulges are parallel to each other indicating that the disks were not randomly accreted at late times (Bender et al. 1993, Scorza & Bender 1995). The high density power-law centers of disky Es (Faber et al. 1997) and the fact these

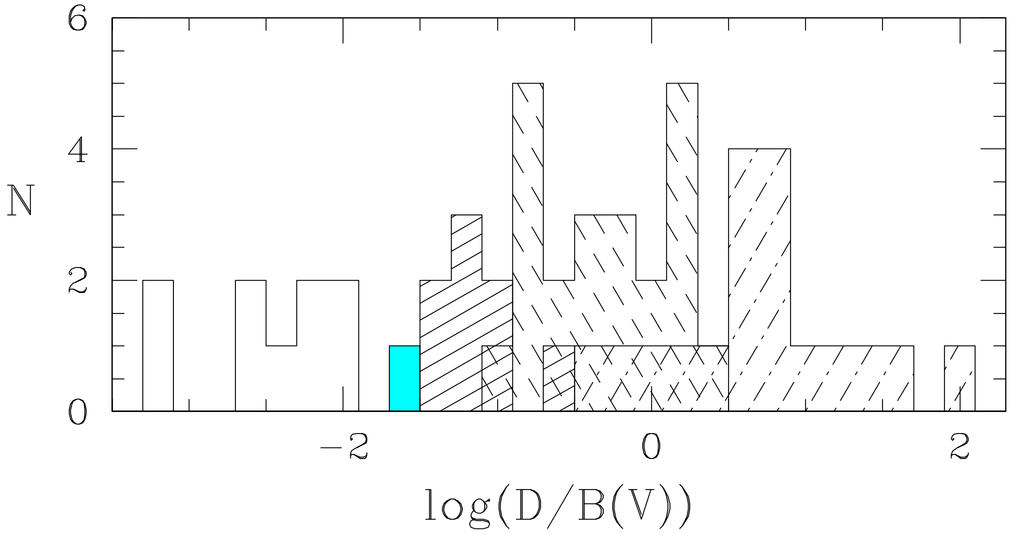

Figure 1. The histogram of the D/B ratios of the (kinematically decoupled) disks of *boxy* galaxies, of *disky* galaxies (full-line shaded), of S0 galaxies (dash-line shaded), and of spiral galaxies (dot-dash line shaded). The position of NGC 5322 is indicated by the grey colour (from Mehlert 1998).

galaxies do indeed harbour disks show that dissipation was essential for their formation. Disky Es simply seem to form the extension of the Hubble sequence to the lowest disk-to-bulge ratios (Bender 1988a, 1990, Kormendy & Bender 1996).

The kinematic structure of boxy Es is generally more complex than the one of disky Es. Peculiar velocity fields, like intrinsic minor axis rotation and kinematically decoupled central regions (Franx & Illingworth 1988, Jedrezjewski & Schechter 1988, Bender 1988b) are frequently found in boxy Es, almost never in disky Es. Intrinsecally peculiar velocity fields are a natural by-product of merging of star-dominated systems (e.g. Hernquist & Barnes 1991; note that projected velocity fields of triaxial bodies can also show peculiarities, see Statler 1994). Unlike shells or ripples (e.g., Schweizer 1990), these features are long-lived and carry 'genetic' information about the formation process of the main (i.e. inner) parts of the galaxy. Kinematic decoupling is generally caused by flattened, rapidly rotating, disk- or torus-like components that dominate the light in the central few hundred pc to kpc (Bender 1990, Rix & White 1992, Surma & Bender 1995, Mehlert et al. 1998). Their masses are of the order 10^9 to 10^{10} $M_\odot$, i.e. only massive mergers can provide enough gas for their formation. The decoupled components do however contribute always less than a few percent to the total light. In fact, the ratio of decoupled-light-to-total-light overlaps with the disk-to-total-light ratios of disky ellipticals at values of about 0.03 (see Fig. 1).

Motivated by this finding one can indeed arrange all galaxies in a disk-to-total sequence ranging from spirals and S0s via disky ellipticals to boxy ellipticals. Towards lower disk-to-total ratios the structures of the galaxies become more and more pressure supported and the anistropy of the spheroidal components may increase as well. Finally, around very low disk-to-total ratios, kinematical decoupling between disks and spheroids sets in. In the most extreme cases, no disk component is formed at all.

2. Scaling relations and global homogeneity

Ellipticals define a two-dimensional manifold in the three-dimensional space of their global structural parameters (effective radius R_e, mean effective surface brightness $< SB >_e$, velocity dispersion σ), the so-called Fundamental Plane (FP, Djorgovski & Davis 1987, Dressler et al. 1987). Its defining relation is $\log R_e = 1.25 \log \sigma + 0.32 < \mathrm{SB} >_e + const.$ (e.g. Jørgensen et al. 1996). It seems to be independent from environment (Burstein et al. 1988, Jørgensen et al. 1996) and is valid for S0s and, with slight changes, for dwarf ellipticals, too (Bender, Burstein & Faber 1992). It is now generally agreed that the FP is simply a consequence of the Virial theorem and the fact that E galaxies have similar mass-to-light ratios and close to homologous structure at a given luminosity (e.g. Faber et al. 1987, Djorgovski et al. 1989, Bender, Burstein & Faber 1992, but see Pahre et al. 1998a, 1998b).

It is very remarkable that, despite of the large variety in internal dynamics and structure, the scatter perpendicular to the FP is as small as observed. Jorgensen et al. (1996) find a typical rms-scatter of 20% in R_e or M/L. In the case of the Coma cluster core, the scatter is smaller than 10% (Saglia et al. 1993, Mehlert 1998). This yields tight constraints on variations in the initial stellar mass function, in dark matter contributions, metallicities and ages, see Renzini & Ciotti (1993), Ciotti et al. (1996), Graham & Colless (1997). Another indicator for the relative homogeneity of ellipticals on the global level is that the objects have close to isotropic velocity distributions (Rix et al. 1997, Gerhard et al. 1998, Kronawitter et al., this conference) and are only mildly triaxial with mostly near oblate shapes (e.g. Franx et al. 1991). This is significantly different from the preferred prolate-triaxial shape of dark matter halos formed in cosmological N-body simulations (e.g. Frenk et al. 1988).

One explanation for the surprising homogeneity of ellipticals on the global level could be the presence of centrally concentrated gas in the merging events Es underwent during their formation. Of similar importance may have been supermassive black holes or steep central density cusps (Gerhard & Binney 1985, Dubinski 1994, Valluri & Merritt 1998). Any sufficiently concentrated central mass will depopulate box orbits in favor of z-axis tubes (Barnes & Hernquist 1996). Box orbits are the backbone of triaxial objects (see e.g. Merritt 1997, Merritt & Quinlan 1998), while z-tubes are dominant in rotationally flattened objects. Scattering of box orbits would preserve disks and decoupled central components but would isotropize the velocity distribution and reduce the triaxiality of the galaxy. If gas fractions or black hole masses are similar for progenitors of similar mass then Es of similar luminosity may have largerly similar phase space structure despite of decoupled cores or disk components. These features are indeed mostly caused by axisymetric components which will not be destroyed by orbit scattering.

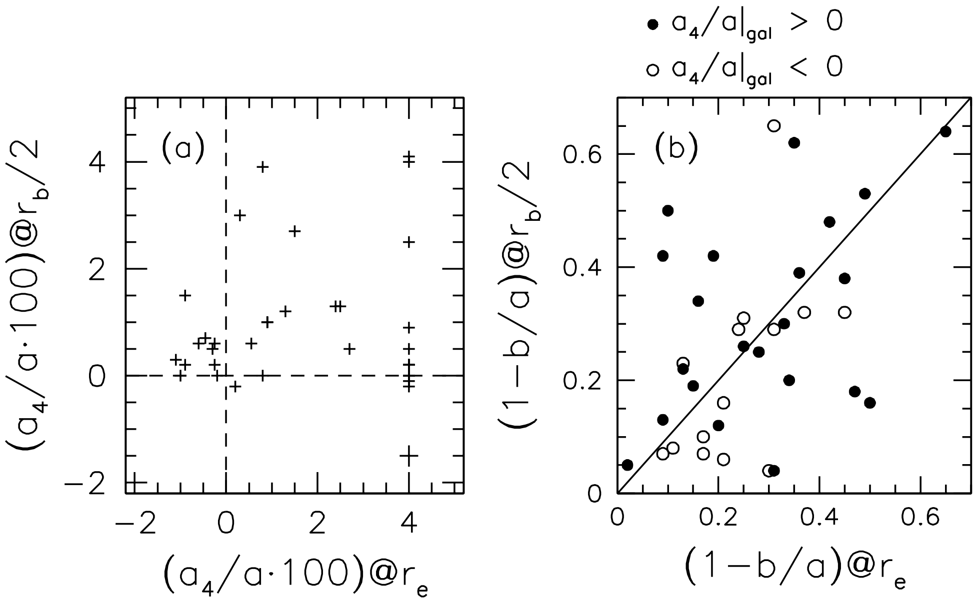

Figure 2. (a) The comparison between the a_4 parameter averaged over r_e and $r_b/2$. (b) The comparison between the ellipticity $1 - b/a$ averaged over r_e and $r_b/2$ (from Tymann 1998). Isophotes inside half the break radius are elliptical or *disky* and no more flattened than the outer regions.

The importance of orbit scattering can be tested by analysing the photometric structure of the innermost regions of elliptical galaxies and comparing it with the one of the main bodies. Orbit scattering should make the inner isophotes rounder and, if boxiness is caused at least in part by box orbits, also more elliptical or disky (Valluri & Merritt 1998). In an analysis of WFPC2 images of elliptical and S0 galaxies from the HST archive, preliminary results by Tymann (1998) show that isophotal shapes of Es and S0s indeed do change around the photometric break radius (for a discussion of break radius and inner light profiles see Kormendy's contribution to this conference). At half the break radius, none of the resolved galaxies is boxy anymore, the isophote shapes are either elliptical or disky (Figure 2). However, isophotes do not become less flattened towards smaller radii. These findings are in part compatible with orbit scattering, but more data and simulations are needed to draw even preliminary conclusions.

3. Stellar Populations and Ages

At any given mass, the stellar populations of elliptical galaxies are remarkably homogenous, consistent with the small scatter about the FP. Colors and line-strengths are generally one-to-one correlated and scale with luminosity or, even more tightly, with velocity dispersion σ (e.g. Burstein et al. 1988, Dressler et al. 1987, Bower et al. 1992, Bender, Burstein & Faber 1993). It is important to note that there is no difference in the Mg$-\sigma$ relation between disky and boxy Es or between kinematically peculiar and regular Es. However, there are hints for a weak dependence of the color$-\sigma$ and Mg$-\sigma$ relations on the presence of rather short-lived peculiarities (due to accretion of younger stars, Schweizer et al. 1990) and, possibly, on environmental density (Guzmán & Lucey 1992, Jørgensen 1997), but generally there is also no significant evidence for a population difference between field and cluster ellipticals of similar velocity dispersion (Colless et al. 1998, Bernardi et al. 1998).

The fact that the Mg-index and colors increase and population gradients steepen with luminosity (e.g. Carollo et al. 1993, Mehlert et al. 1999a, 1999b) are further strong evidence that a merging picture without dissipation does not work.

Using stellar population synthesis models (e.g., Worthey 1994) one can estimate the combined scatter in age and metallicity from the observed scatter in the color$-\sigma$ or Mg$-\sigma$ relations (e.g. Bower et al. 1992; Bender, Burstein & Faber 1993). The strongest constraints however follow from a combined analysis of the scatter around the FP and the Mg-σ-relation. Colless et al. (1998) note that while the FP scatter is most sensitive to the scatter in age, the Mg-σ scatter is most sensitive to the scatter in metallicity of the stellar populations. Figure 3 (Mehlert 1998, Mehlert et al. 1999a, 1999b) shows how the combined small scatters of the Mg-σ and FP of the Coma cluster early-type galaxies allow for no more than $\approx$20 % scatter in relative metallicity and age at a given σ. The constraint is even tighter for the sample of galaxies of the core of the cluster, where $\delta t/t \approx 10\%$.

This is consistent with the current observations of elliptical galaxy evolution as a function of redshift. The color-magnitude relation (Standford et al. 1998) up to $z \approx 1$, the Mg-σ-relation (Bender et al. 1996, Ziegler & Bender 1997) up to $z \approx 0.4$, and the FP relation (van Dokkum & Franx 1996, Kelson et al. 1997, Bender et al. 1998, van Dokkum et al. 1998) up to $z \approx 0.8$ all seem to be compatible with *passive* evolution, implying high formation redshifts.

The age constraints for lower luminosity Es, which mostly belong to the disky class, are less tight due to smaller samples or larger scatter in Mg and colors at smaller σ. In fact, it is indicated 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 (1996). Note that this trend runs opposite to the one expected in a cold-dark-matter model (Kauffmann et al. 1997, Kauffmann 1998, Baugh et al. 1998). The apparently smaller ages of low luminosity Es could in fact be caused by the faint disks they contain. These disks may become more dominant towards lower luminosities and may have had extended star formation histories. Hints for this have been found by de Jong & Davies (1997).

4. Abundance Ratios and Star Formation Time Scales

Another way to extract information about the star formation history of ellipticals is to analyse their element abundance ratios. For *luminous* Es, Worthey et al. (1992), Davies et al. (1993), Mehlert et al. (1998) and others found consistently

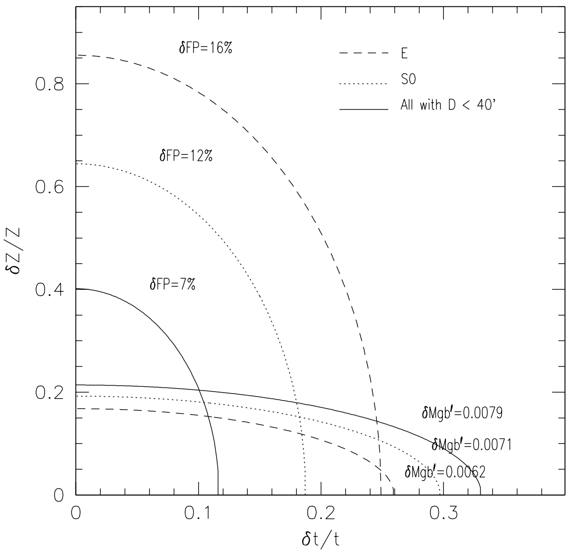

Figure 3. The global constraints on the scatter in age and metallicity from the combined scatter of the Mg-σ and FP relation (from Mehlert 1998).

that Mg is overabundant relative to Fe. Over a larger luminosity range, [Mg/Fe] seems to be correlated with velocity dispersion: faint Es have [Mg/Fe]≈ 0, while luminous Es reach [Mg/Fe]≈ 0.4 (Gonzalez 1993, Fisher, Franx & Illingworth 1995). Furthermore, Paquet (1994) could show that, in luminous Es, other light elements like Na and CN are overabundant relative to Fe as well. Within the galaxies, the [Mg/Fe] overabundance is usually radially constant up to at least the effective radii (Davies et al. 1993, Mehlert et al. 1998, Paquet 1994). Generally, no distinction between 'normal' luminous Es and Es with kinematically decoupled cores is indicated.

These results imply that the enrichment history of luminous Es differed significantly from the one of the solar neighborhood, see e.g., Matteucci & Greggio (1986), Truran & Burkert (1995), Faber et al. (1995), Worthey (1996).

Evidently, the enrichment of *massive* (high velocity dispersion) Es was dominated by Supernovae II, as only they can produce a light element overabundance. Supernovae Ia basically just provide iron peak elements (see, e.g., Truran & Thielemann 1986). Because the yields of SNII integrated over a plausible IMF result in [Mg/Fe]≈ 0.3 dex at most (see Thomas, Greggio & Bender 1998a), we can conclude that the contribution of SNIa to the enrichment of the most massive Es must have been small.

The prevalence of Supernovae II and in turn the light element overabundance in massive Es can have the following reasons: (a) a star formation time scale smaller than about 1Gyr (SNI explode in significant numbers only after a few times 10^8yrs after star formation started, e.g. Truran & Burkert 1995), (b) a top heavy initial mass function, (c) a reduced frequency of binary stars (lead-

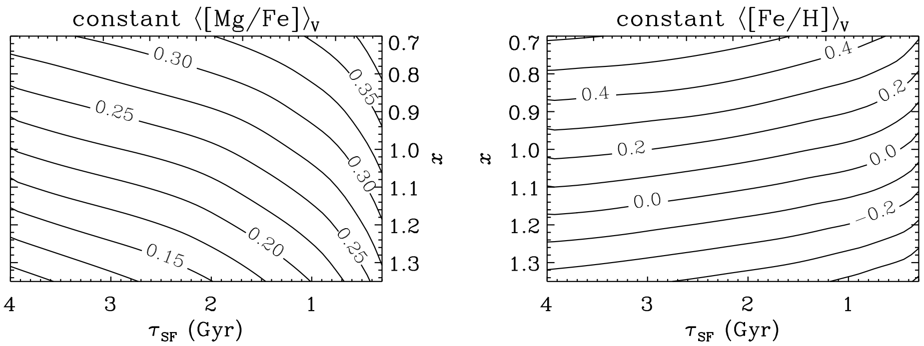

Figure 4. The contours of constant $\langle[\mathrm{Mg/Fe}]\rangle_V$ (left) and of constant $\langle[\mathrm{Fe/H}]\rangle_V$ (right) as a function of the star formation time-scale τ_{SF} and the slope of the IMF. Long star formation time scales cannot be reconciled with the high Mg/Fe overabundance pbserved in elliptical galaxies even with a modestly flat IMF (from Thomas et al. 1998b).

ing to fewer SNI events). – Option (c) is rather unlikely because one expects the binary frequency to be determined by the local process of star formation rather than by global galaxy properties. In addition, a low binary fraction may be inconsistent with the observed frequency of discrete X-ray sources in old populations. Neither does option (b) work well, because the overabundance in massive Es reaches [Mg/Fe]$\approx$ 0.4 dex (as is also observed in Galactic halo stars, Fuhrmann et al. 1995). For such high overabundances, a flat IMF alone cannot solve the overabundance problem. So, option (a), i.e. a short star formation time scale, seems to be necessary in any case. In their recent study, Thomas, Greggio & Bender (1998b) show that the star formation time scale in massive Es was probably shorter than about 1Gyr. Using a shallower IMF this time can be somewhat extended but gets in conflict with the observed abundance of iron in most ellipticals, which is about solar (see Fig. 4).

Note that these considerations do not only apply to the cores of luminous Es but for the bulk of their stars, since the [Mg/Fe] overabundance is similar at all radii (see above). And another important conclusion can be drawn from these findings: since most present day spirals have gas-to-star ratios smaller than 0.2 and disk stars show solar element ratios, merging of objects similar to present-day spirals cannot produce objects similar to most present-day massive Es.

Since lower luminosity ellipticals have smaller light-element overabundances, their star formation time scales are not severely constrained. In fact, solar element abundance ratios could be taken as a hint for extended star formation histories in smaller Es.

5. Observations *vs.* hierarchical galaxy formation

In hierarchical galaxy formation scenarios galaxies are expected to form via a sequence of merging and accretion processes (e.g. White 1993). Merging is a key driver of star formation depleting the gas with increasing galaxy mass (e.g.

Katz 1992, Steinmetz & Müller 1994, Kauffmann 1998, Baugh et al. 1998). Mergers with mostly stellar progenitors are supposed to form ellipticals and are more likely to occur if the progenitors are more massive. Note that the stellar population properties (e.g. Mg-σ-relation, Mg-gradients etc.) require that some gas must have been involved in the formation of basically all ellipticals (see above).

The amount of gas present during a merger can have significant influence on the dynamical structure of the merger product. As discussed above, centrally concentrated gas, likewise density cusps or black holes, will depopulate box orbits. For some objects the gas fraction or central density concentration will be so low that a 'phase transition' from parallelized angular momenta of disky and spheroidal components to kinematical decoupling can occur. Simply speaking, less concentration implies a more exciting end product. In this scenario, disky Es are merger products as well but a higher gas fraction helped to produce objects with properties similar to what is expected from a *single* dissipative collapse (e.g. Larson 1975). Consistent with this scenario, the vast majority of boxy Es (except for a small sub-class of boxy companions to bright galaxies) has luminosities above L_*, while the luminosity function of disky Es resembles the one of S0s (Bender et al. 1993). As to be expected in hierarchical galaxy formation, there is a variety of paths to form objects of similar mass and this is why ellipticals of similar luminosity can show quite different detailed properties. *This fact also implies that for any given elliptical, isophotal shape may be a better indicator for the formation history than luminosity.*

The low-redshift analogue of the late formation-phase of boxy Es may be found in ultraluminous IRAS mergers (Schweizer 1990, Kormendy & Sanders 1992, Bender & Surma 1992). Numerical simulations with large particle numbers indicate that dissipationless violent relaxation alone may indeed create boxy main bodies (Steinmetz 1995). Furthermore, Bekki & Shioya (1997) found indications that the rapidity of the gas consumption during the merger may influence the isophotal shape of the remnant. In their simulations, rapid star formation produced boxy isophotes, slow star formation disky isophotes. A large fraction of the molecular gas of the progenitors concentrates in the central kiloparsec and can form a kinematically decoupled center (Hernquist & Barnes 1991, Barnes 1996). Indeed, the masses and metallicities of kinematically decoupled centers in Es are quite similar to those of the central gas tori in IRAS mergers (Sanders, Scoville, Soifer, 1991; Bender & Surma 1992, Mehlert et al. 1998). We can speculate that very gas-rich progenitors (and/or slow star formation during the merger (Bekki & Shioja 1997) may also create disky Es, especialy if gas falls in at late times from large radii (Hibbard & van Gorkom 1996). The analogy of E galaxy formation and the IRAS merging process is unlikely to be perfect. Especially, it does not necessarily imply that many field Es formed in spiral-spiral mergers at low redshift – merging of any star-dominated progenitors at any redshift may have produced similar remnants.

While the structural properties of ellipticals naturally arise in a hierarchical model of galaxy formation, the stellar population properties of ellipticals pose more of a challenge. The generally high overabundances of light elements over Fe in massive ellipticals indicate very short star formation time scales and are in conflict with forming a significant fraction of field ellipticals in late mergers.

Furthemore, the fact that low luminosity ellipticals appear to be younger than high luminosity objects needs a convincing explanation.

There is still the other possibility that current stellar population models do not explain absorption indices accurately enough to determine overabundances with sufficient reliability. If the true overabundances in massive ellipticals are significantly lower than current estimates, then this relaxes the observational limit on more extended star formation at lower redshifts significantly.

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