ELLIPTICAL GALAXIES

https://doi.org/10.1017/S0074180900232130 Published online by Cambridge University Press

THE STAR FORMATION HISTORY OF ELLIPTICAL GALAXIES

ROGER L. DAVIES
Department of Physics, University of Durham,
South Rd., Durham, U.K., DH1 3LE.

Abstract. There is a growing body of evidence indicating young ages, 8 ± 3 Gyrs, for elliptical galaxies and significant age gradients with a younger population residing at the centre. The data appear to be consistent with a scenario where elliptical galaxies are assembled hierarchically with low luminosity galaxies forming first. Late star formation, associated with the last merging event and usually involving only a small fraction of the galaxy mass, could then account for the low age estimates of some luminous galaxies.

1. Introduction

Conventionally elliptical galaxies are thought to be are old and coeval, having experienced an initial burst of star formation about 15 Gyrs ago, with little or no star formation since. An increase in mean metallicity with luminosity then accounts for the observed systematic variation in galaxy properties with luminosity, for example the colour magnitude relation. The principle empirical problem in testing this scenario is that the observational effects of a decrease in metallicity and a decrease in age are degenerate.

In contemporary cosmologies where dark matter halos evolve through a sequence of hierarchical mergers, low luminosity ellipticals form before their brighter brethren. Luminous elliptical galaxies form late (at say $z \sim 0.5$) by the merging of old, mostly *stellar* subsystems. Some observations, such as the existence of dynamically decoupled cores and the first results of cosmological simulations including gas physics, suggest that this merging process can be accompanied by star formation. Bender, Burstein & Faber, 1992, have suggested that many dynamical and stellar population characteristics of ellipticals can be accounted for if gas dissipative processes are more important in the evolution of low luminosity systems and stellar, dissipa-

R. Bender and R. L. Davies (eds.), New Light on Galaxy Evolution, 37–45.

https://doi.org/10.1017/S0074180900232130 Published online by Cambridge University Press

tionless process dominate in luminous ellipticals. In order to understand the dominant physical processes in galaxy evolution we need to date the star formation episodes in elliptical galaxies and estimate the mass involved at each stage of star formation activity.

From this written record of the review I have omitted the discussion of the important work on M32 which I have discussed elsewhere (Davies, 1996).

2. The Uniformity of Elliptical Galaxies

2.1. STRUCTURE & DYNAMICS

Elliptical galaxies are remarkably uniform, they have smooth luminosity profiles with no azimuthal structure (Peletier *et al*, 1990). They are well fit by an $R^{\frac{1}{4}}$ law with residuals of typically less than 0.1 magnitudes over $R < 4R_e$. Van Albada, 1982, has used N-body simulations to show that such an $R^{\frac{1}{4}}$ profile arises from the dissipationless collapse and violent relaxation of an initially clumpy distribution of stars. The most significant residuals from an $R^{\frac{1}{4}}$ law (typically less than a few % of the light of any isophote) are the boxy and disky distortions that show up most clearly in the analysis of the isophote shapes.

The tight relationship between the central velocity dispersion, σ, effective radius, R_e & effective surface brightness, I_e, of elliptical galaxies, the "Fundamental Plane", discovered by Djorgovski & Davis (1987) & Dressler *et al* (1987) sets constraints on mass-to-light ratio changes amongst the population of ellipticals and therefore constrains variations in their star formation history. The typical scatter is $\sim 20\%$ in R_e, for galaxies in the Coma cluster Jorgensen, Franx & Kjaergaard (1993) report that the scatter is 11%. Renzini & Ciotti (1993) have explored the thickness and tilt of the FP, they conclude that at any location in the FP the thickness of the plane limits the dispersion in M/L to 12% and that the tilt of the plane implies a variation in M/L amongst ellipticals to less than a factor of three. The star formation history of elliptical galaxies gives rise to remarkable degree of structural and dynamical homogeneity.

2.2. SPECTROPHOTOMETRIC PROPERTIES

Sandage & Visvanathan (1978) demonstrated the systematic reddening of elliptical galaxies with increasing luminosity. Elliptical galaxies also become redder and have stronger metal absorption lines with decreasing radius (Faber, 1977, Cohen, 1979). These observations led to the suggestion that *both* effects were driven by increases in metallicity. The tightness of the colour magnitude relations for galaxies in clusters has been emphasised by

https://doi.org/10.1017/S0074180900232130 Published online by Cambridge University Press

Bower et al (1992) and Renzini (1995) as putting tight constraints in the possible spread in age amongst cluster ellipticals. Recently near infrared surface photometry, has shown that the colours of disks and bulges are similar (Terndrup *et al* 1994, de Jong 1995). This may indicate that the *old* stellar population in ellipticals, bulges & disks have similar ages and metallicities.

There is a remarkably tight relationship between the central Mg_2 line strength and the central velocity dispersion in ellipticals:

$$Mg_2 = 0.2\text{Log}\sigma - 0.166$$

The scatter corresponds only 20-30% in metallicity. This tight relationship may arise from special processes that occur in the centres of galaxies, however the tightness of the relationship between a dynamical parameter and one that arises entirely through the physics of stellar evolution suggests a remarkably close connection between the chemical and dynamical evolution of ellipticals.

3. Late Star Formation in Elliptical Galaxies?

There have been hints for many years that some elliptical galaxies have experienced star formation much less than a Hubble time ago. Larson, Tinsley and Caldwell (1980), showed that while cluster galaxies exhibit a tight colour magnitude diagram, those in the field show more scatter, which they attributed to late star formation in galaxies in low density environments. Similarly Schweizer *et al*, 1990, showed that galaxies with well developed symptoms of past interactions, jets, shells, etc. have stronger $H\beta$ and weaker metal lines than those that appear to have had a calmer history. They interpreted this in terms of late star formation in the disturbed objects. At high redshift, direct evidence that star formation in cluster environments continued until relatively recently is provided by the observation that the fraction of blue galaxies in clusters of redshift $\sim \frac{1}{2}$ is much higher than it is at zero redshift (Butcher & Oemler 1978).

In recent years a number of in depth studies have attempted to combine high metallicity isochrones and models of stellar atmospheres, with spectral libraries of high abundance stars and models of post main sequence evolution, to produce predictions of the spectral energy distribution (SED) of the integrated light of elliptical galaxies. These models span a range of philosophies, some provide model SEDs for populations of a given metallicity and age such as Peletier (1989), Buzzoni (1989,1995), Bruzual & Charlot (1993) and Worthey (1994), others take into account the large spread in metallicity expected in ellipticals eg. Arimoto &Yoshii 1987; the most ambitious also include the effects of galaxy evolution eg. Bressan, Chiosi & Fagotto

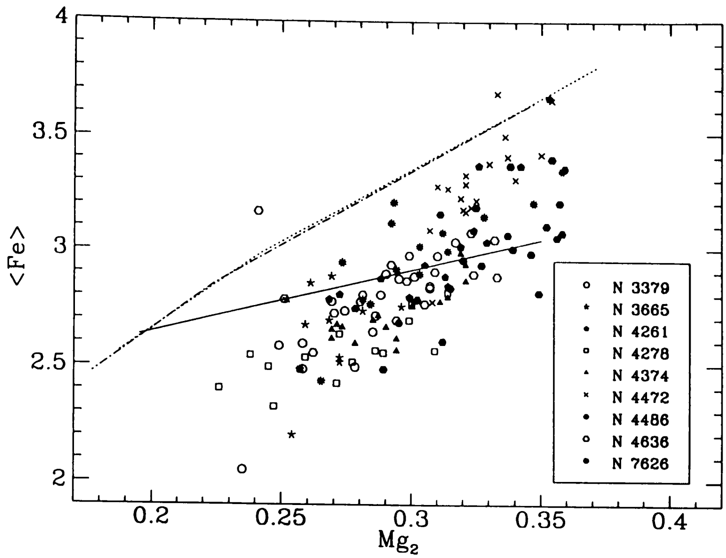


Figure 1. The variation of the mean of two iron features, $< Fe >$, plotted against Mg_2 for points within 9 elliptical galaxies. The solid line is the fit to the cores of elliptical galaxies taken from Burstein *et al 1984*. Two models of single age stellar populations (with ages 12 & 20 Gyrs) from Peletier (1989) are plotted as dash-dot and dotted lines, each spanning a range of metallicity from 0.25 to 2.5 times solar.

(1994). However it remains difficult to unambiguously separate the effects of younger age from those of decreased metallicity, especially in luminous galaxies where the sensitivity of the measurements is reduced by the high velocity dispersions which blend and broaden absorption features. Some results are however emerging.

3.1. NON-SOLAR ABUNDANCE RATIOS

The simplest interpretation of the increase in line strengths with decreasing radius and increasing luminosity (or σ) is an increase in [Fe/H], the single parameter metallicity. Spectral features would then be expected to strengthen in "lockstep" as metallicity increased. It has become clear that no models with solar abundance ratios can account simultaneously for the variation of Mg_2 to Fe within and between elliptical galaxies (Peletier 1989, Gorgas, Efstathiou & Salamanca, 1990, Worthey, Faber & González, WFG, 1992, Davies, Sadler & Peletier, (DSP), 1993). This is illustrated in Figure 1, taken from DSP, which shows the variation of Fe against Mg_2.

The measured points do not correspond to models with solar ratios of Fe to Mg, but are shifted to higher values of Mg at fixed Fe. WFG draw the same conclusiopn using their models. The discrepancy cannot be accounted for by reducing the age as the effects of decreasing age and lowering the metallicity are the same in this diagram. It appears that either magnesium is enhanced or iron depleted compared to solar values throughout the giant galaxies. Similarly it is clear that the trend from galaxy to galaxy exhibits a shallower slope than that found within galaxies and on this basis we would expect the low metallicity galaxies (with $Mg_2 \sim 0.2$) to have roughly solar ratios which WFG find to be the case. For an explanation of these anomalies we look to the processes that produce iron & magnesium. Mg is produced predominantly in massive (20-40 M_{solar}) Type II supernovae (Woosley & Weaver 1986), their lifetimes are typically 10 million years, whereas Fe is produced in both Type II and in Type Ia supernovae. The low mass stars that give rise to Type Ia SN have lifetimes typically a few hundred times longer than the Type II progenitors and these provide the dominant source of Fe in old populations. There are several ways in which the galaxies with strong absorption lines might have an excess ratio of Mg/Fe compared to solar values:

1. The stars that dominate the V-band light output were formed in a short burst after which star formation ceased. This would produce a population enriched in Mg from rapid, Type II supernovae. Stars (with solar abundance ratios) would not be formed from the Fe enriched gas generated by Type Ia supernovae.
2. The Initial Mass Function was skewed to more massive stars in comparison to the solar neighbourhood, this would require the IMF to vary continuously from the giants to low luminosity ellipticals which do not exhibit the abundance anomaly.
3. Fe-rich gas produced by Type Ia SN is lost through the onset of a galactic wind that is established after Mg production but before significant Fe production. This would imply an *over*-abundance of Fe in the hot IGM. The status of measurements of the abundance of Fe in the IGM, infered from ASCA spectra, is discussed by Arimoto elsewhere in this volume.
4. The star formation processes in ellipticals produced fewer binary stars, this is unlikely given the observed nova rates and LMXB populations.
5. Metal rich SN could produce higher ratios of [Mg/Fe], (Peterson, 1976).

It is not clear how a short, early burst of star formation fits into hierarchical galaxy formation models where the stars that are assembled into giant galaxies formed in a range of localities. Nevertheless, wherever they formed, if the process was rapid and there was no subsequent star formation (perhaps because the system was disrupted) the abundance anomaly would be established.

3.2. THE AGES OF ELLIPTICAL GALAXIES

To separate the effects of age and metallicity we need to identify colours or absorption line features which change differentially with metallicity changes at constant age, compared to age changes at fixed metallicity. Worthey (1992), for example, showed that while the weak Fe features in the Faber-Burstein indices are the most sensitive to metallicity they are difficult to measure accurately leaving the widely used Mg_2 as a practical indicator. He found that $H\beta$ is relatively insensitive to metallicity and can be used as an age indicator, the largest drawback being the correction for emission observed in many galaxies. Buzzoni (1989, 1995) and Buzzoni, Gariboldi & Mantegazza (1992, 1994) have generated models that produce almost the same effects in Mg_2 and $H\beta$. In his thesis González (1993), reports line strength gradient measurements in 41 ellipticals. He applied Worthey's models using a mean MgFe index (to reduce the effect of the magnesium overabundance) and $H\beta$ to estimate ages/metallicities. He made an empirical correction for the $H\beta$ emission based on the emission in O[III]. He shows that the mean stellar age of the bulk of ellipticals is 8 ± 3 Gyrs. He also found that the inner regions of elliptical galaxies are younger by about 3 Gyrs than the outer parts. These results are reported and amplified in WFG and Faber, Trager, Gonzalez & Worthey, 1995. These age estimates are uncomfortably low for galaxies that were thought to form 15 Gyrs ago in a single burst of star formation. There are two possible systematic effects which could account for the high values of $H\beta$ absorption which drive these authors to low age estimates. The first is the possibility that the correction for $H\beta$ emission is too large, Carrasco (1996) shows that $H\beta$ emission varies with radius in ellipticals and rarely corresponds to Gonzalez prescription. The second possibility is that the high $H\beta$ values arise not from stars at the tip of the main sequence, but from blue horizontal branch stars and therefore $H\beta$ is not a good age indicator. This would seem to be unlikely in a metal rich population although it may be that a considerable range of metallicity exists in elliptical galaxies and therefore BHB stars may contribute.

Elsewhere in this volume (Halliday *et al*) we report preliminary measurements of line strength gradients in low luminosity ellipticals. The data for NGC 4478 are shown in Figure 2. The same age gradient, with a younger population in the centre, is apparent as is found in the luminous galaxies. We have made preliminary estimates of the ages and metallicities of the LLEs relative to the giant ellipticals. We find metallicities down by factors of 4-6 and ages, for the bulk of the galaxy, to be 20-40% older (or the last star formation occurred that much longer ago) than in the corresponding regions of the luminous galaxies. This appears to support a hierarchical

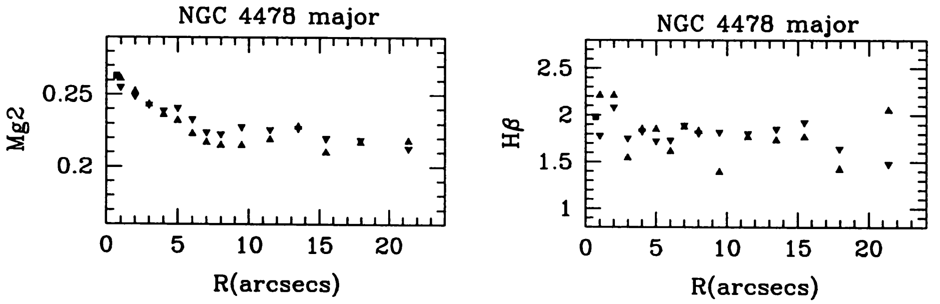


Figure 2. Gradients in the Mg_2 and $H\beta$ indices along the major axis of NGC 4478. These are preliminary measurements on the Faber-Burstein scale but not corrected for velocity dispersion effects.

picture where the low luminosity systems experienced their last merger at an earlier stage in their evolution and, associating this merger event with the last opportunity for star formation, we expect their distribution of ages to be skewed to larger values, as we observe.

Gas accreted in mergers would be likely to have high angular momentum (from the relative orbit) and so we might expect any associated star formation to be distributed in a disk. (Franx & Illingworth (1989) made this suggestion to account for the peculiar core kinematics of IC1459). With de Jong, I have tested this hypothesis (reported elsewhere in these proceedings) by examining the isophote shapes for galaxies with measured $H\beta$ strengths. As shown in the figure in our poster we find that there is a tendency for galaxies with stronger $H\beta$ to have disky isophotes. This result is at least consistent with the $H\beta$ arising from stars formed in gas accreted in a merger.

So how old are the stars in *luminous* elliptical galaxies? Gonzalez' results indicate a large spread of ages for galaxies with essentially the same metallicity. Hierarchical models of galaxy formation assemble the most massive galaxies latest, therefore if we hypothesise that star formation is sometimes associated with a merger event, then we may conclude that the luminous ellipticals with stronger $H\beta$ lines experienced a burst of star formation associated with their last merger and those with weaker $H\beta$ lines did not.

The age of the *oldest* stars in ellipticals, (this is certainly what we mean when we estimate the "age" of the Milk Way even though the oldest population, the globular clusters, provide an insignificant fraction of the total luminosity), remains uncertain.

4. Conclusions & Questions

1. Elliptical galaxies exhibit a high degree of structural and dynamical uniformity, some of this arises from identified physical process eg. violent relaxation. If ellipticals experience a turbulent star formation history associated with a merging hierarchy how is this uniformity retained?
2. The light elements and Fe peak elements appear not to occur in their solar ratios in luminous ellipticals. The relationship between Fe and Mg line strengths *within* galaxies does not follow the same trend as is found *between* galaxies suggesting a different physical origin. Rapid star formation will produce Mg quickly in Type II supernovae. If star formation is truncated, no significant population will form from gas enriched in Fe, and a Mg overabundance will result. This also implies that the V-band light of elliptical galaxies is dominated by a stellar population that was formed in a single burst. What physical processes control the Fe/Mg ratio in ellipticals?
3. The large range of ages for ellipticals of a given metal line strength, the age gradients, the older age estimates of LLEs and the tendency for galaxies with high $H\beta$ to have disky isophotes, all support a scenario where galaxy formation proceeds in a merging hierarchy in which late star formation, involving only a small fraction of the galaxy mass, is sometimes associated with the mergers.

References

Arimoto N. & Yoshii Y., 1987, A&A, 173, 23.
Bender R., Burstein D. & Faber S.M., 1992, ApJ, 399, 462.
Bower, R. G., Lucey, J. R., & Ellis, R. S., 1992, MNRAS, 254, 601.
Bressan A., Chiosi C. & Fagotto F., 1994, ApJ Supp, 94, 63.
Bruzual G.A. & Charlot S., 1993, ApJ, 405, 538.
Burstein D., Faber S.M., Gaskell C.M. & Krumm N., 1984, ApJ, 287, 586.
Butcher H. & Oemler A., 1978, ApJ, 219, 18.
Buzzoni A., 1989, ApJ Supp, 71, 817.
Buzzoni A., 1995, ApJ Supp, 98, 69.
Buzzoni A., Gariboldi G. & Mantegazza L., 1992, AJ, 103, 1814.
Buzzoni A., Gariboldi G. & Mantegazza L., 1994, AJ, 107, 513.
Carrasco M., 1996, in Proceedings of "Fresh Views of Elliptical Galaxies", P. 235, ASP Conf. Series No.86 (San Francisco, ASP), eds. A. Buzzoni, A. Renzini and A. Serrano.
Cohen J.G., 1979, ApJ, 228, 405.
de Jong R.S., 1995, PhD Thesis, University of Groningen.
Davies R.L., Sadler E.M. & Peletier R.F., 1993, MNRAS, 262, 650.
Davies R. L., 1996, in Proceedings of "Fresh Views of Elliptical Galaxies", P. 175, ASP Conf. Series No.86 (San Francisco, ASP), eds. A. Buzzoni, A. Renzini and A. Serrano.
Dressler A., Lynden-Bell D., Burstein D., Davies R.L., Faber S.M.,Terlevich R.J. & Wegner G., 1987, ApJ, 313, 42.
Djorgovski S. & Davis M., 1987, ApJ, 313, 59.
Elston R. & Silva D., 1992, AJ, 104, 1360.

https://doi.org/10.1017/S0074180900232130 Published online by Cambridge University Press

Faber S.M., 1977, in *"The Evolution of Galaxies and Stellar Populations"*, Yale University Press, p157, ed. Tinsley B.T. & Larson R.B.
Faber S. M., Trager S. C., Gonzalez J.J. & Worthey G., 1995, in *"Stellar Populations"*, IAU Symp. 164, ed. G. Gilmore & P. van der Kruit, (Kluwer).
Franx M. & Illingworth G.D., 1990, ApJ Lett, 359, L41.
González J.J., 1993, PhD Thesis, University of Santa Cruz.
Gorgas J., Efstathiou G. & Aragón Salamanca A., 1990, MNRAS, 245, 217.
Jørgensen I., Franx, M., & Kjærgaard, P., 1993, , 411, 34.
Larson R.B., Tinsley B.M. & Caldwell C.N., 1980, ApJ, 237, 692.
Peletier, 1989, PhD Thesis, University of Groningen.
Peletier R.F., Davies R.L., Illingworth G.D., Davis L. E. & Cawson, 1990, AJ, 100, 1091.
Peterson, R., 1976, ApJ, 210, L123.
Renzini A., & Ciotti, L., 1993, ApJ Lett, 416, L49.
Renzini A., 1995, in *Stellar Populations*, Proc. of IAU Symp 164, P. 325, ed. Gilmore G. & van der Kruit P., (Kluwer).
Sandage A.R. & Visvanathan N., 1978, ApJ, 225, 742.
Schweizer F., Seitzer P., Faber S.M., Burstein D., Dalle Ore C. & González J.J., 1990, ApJ Lett, 364, L33.
Terndrup D.M., Davies R.L., Frogel J.A., Depoy D.L., & Wells L.A., 1994, ApJ, 432, 518.
van Albada T. S., 1982, MNRAS, 201, 939.
Woosley S.E. & Weaver T.A., 1986, Ann. Rev. A&A, 24, 205.
Worthey G., Faber S.M. & González J.J. (WFG), 1992, ApJ, 398, 69.
Worthey G., 1994, ApJ Supp, 95, 107.

Discussion

Tim de Zeeuw: What would the luminosity weighted age of our own galaxy be?

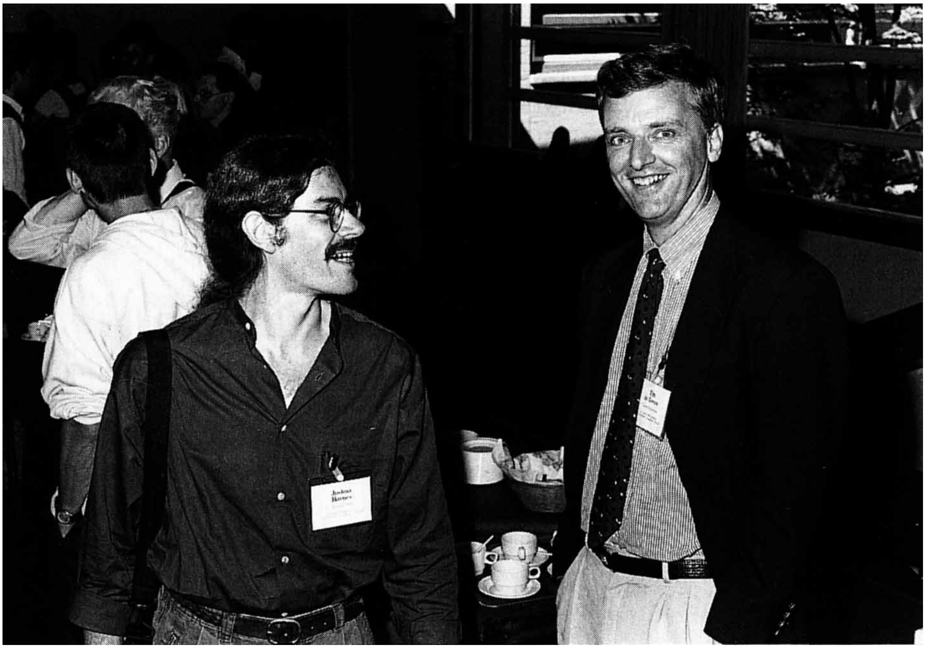
Roger Davies: The star formation rate in our own galaxy's disk has been roughly constant over its age, so it would be roughly 5Gyrs, younger if luminosity weighted in the *blue*.

Marshall McCall: Both the ages and metallicities are luminosity weighted. Is it possible that this weighting varies with metallicity? Is it possible that Mg is weighted differently from Fe? What stars are setting the metallicity we "see" in ellipticals?

Roger Davies: In general we would expect the luminosity weighting to be a function of metallicity. It is unlikely that Fe and Mg will be weighted differently as they arise in the atmospheres of stars of rather similar temperatures namely G, & K-giants, these are the stars that dominate the metallicity determination.

Hans-Walter Rix: You have shown how degenerate the SED is to age/metallicity trade-offs. Is there any hope of breaking this degeneracy by considering the colour dependence of surface brightness fluctuations?

Roger Davies: In principal yes, calculations of the SBFs were made by Worthey in his thesis.



Josh Barnes and Tim de Zeeuw