MEASURING THE EVOLUTION OF THE M/L RATIO FROM THE FUNDAMENTAL PLANE

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Abstract. The Fundamental plane provides a sensitive tool to measure the change in the M/L ratio of early type galaxies with redshift. The evolution of the M/L ratio is a function of the star formation history. It depends on the IMF, the formation redshift, and cosmology. Some model examples are shown, and a first result on the cluster Abell 665 at z=0.18 is given. The measurements confirm the cosmological surface brightness dimming, and imply an evolution of the (red) L/M ratio $\propto (1+z)^{1.8\pm0.7}$. More data are needed to extend this result to higher redshifts, and to test the underlying assumptions.

1. Introduction

A good understanding of the mass-to-light ratios of galaxies, and their stellar populations is very valuable. They are needed for a proper understanding of the galaxy dynamics, dark matter distribution, distance indicators, and matter content of the universe in general.

Studies of nearby early type galaxies have shown that their central M/L ratios are very regular: $M/L \propto r_e^{0.25}\sigma^{0.44}$, where r_e and σ are the effective radius and central velocity dispersion of the galaxy (Faber *et al.*, 1988). This follows directly from the existence of the "Fundamental Plane", which is a relation between the structural parameters r_e, σ, μ_e of the form $r_e \propto \mu_e^{-0.8}\sigma^{1.25}$ (Dressler *et al.*, 1987; Djorgovski and Davis, 1988). The parameter μ_e is the surface brightness of the galaxy.

The cause of the relation is not well understood, but it is thought to be due to systematic metallicity differences between galaxies (e.g., Faber *et*

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al., 1988; Renzini and Ciotti, 1993). The relation can be used to measure distances to galaxies (under the assumption of a "Universal Fundamental Plane").

Here we focus on the evolution of the M/L ratio with redshift. The M/L ratio of a galaxy must evolve, because the giants, which contribute significantly to light, have a short lifetime compared to the Hubble time. The light from this population therefore depends strongly on the rate at which stars turn off from the main sequence.

2. Evolution of the luminosity with redshift

The evolution of the M/L ratio is dominated by the evolution of the luminosity with time, as the mass remains constant (ignoring mergers). In the following, we therefore use the inverse ratio L/M, instead of the M/L.

Various models were analyzed to estimate the dependence of the luminosity with time. For this purpose, we used the models by Buzzoni (1989), and Worthey (1994). Both authors calculated luminosities for a wide variety of models, with a range in metallicities and IMF. These models predict that the luminosity evolves like a power law: $L_R \propto t^{-0.83\pm0.15}$, where the coefficient depends somewhat on the IMF (as predicted by Tinsley, 1972, 1980), and the metallicity.

The rapid evolution of the luminosity implies that the L/M evolves rapidly with time. Hence the small scatter in observed L/M ratios implies a small scatter in the ages of early type galaxies (Renzini and Ciotti, 1993). The scatter of 10 % in the Fundamental Plane measured in the Coma cluster (Lucey *et al.*, 1991; Jørgensen *et al.*, 1993) translates into a scatter of 15% in the age. This is the scatter at a given σ and r_e, the age can still vary as a function of σ and r_e.

The evolution of the L/M ratio of a co-eval population as a function of redshift is a function of the formation redshift z_{form}, and q_0. Fig. 1a shows two examples of the predicted evolution, for formation redshift of 1 and 100. Very clearly, the evolution depends strongly on the formation redshift. A good approximation is

$$\ln L/M\ (z) - \ln L/M\ (0) = 0.83\ (1 + q_0 + 1/z_{form})\ z \qquad (1)$$

where the coefficient of 0.83 is the logarithmic derivative of the luminosity with time $d\ln L/d\ln t$. The luminosity evolution can be twice as fast for formation redshift ≈ 1, compared to very high formation redshift.

Identical expressions will hold for other indicators of the stellar population which evolve like power laws. The colors and absorption line indices are such parameters. The evolution of these parameters will be described by an equation of form (1). The coefficient of 0.83 needs to be replaced by $d\ln(index)/d\ln t$.

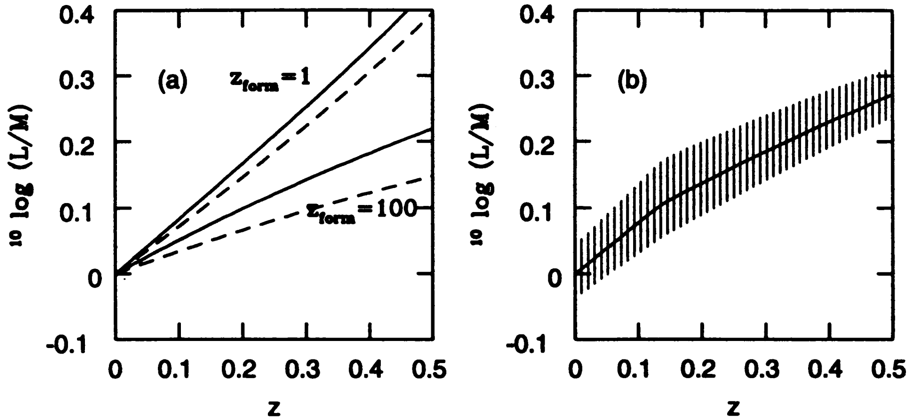

Figure 1. a) The predicted evolution of the L/M ratio for co-eval populations. The drawn lines are for formation redshifts z_{form} of 1 and 100. The dashed curves show the apparent L/M ratio when the true value of q_0 is 0. The observed evolution is a function of both z_{form} and q_0. b) The evolution of the L/M ratio if the formation history is complex. Galaxies are assumed to evolve like disks, with a star burst at the end. The star burst can occur between z=0.3 and 2. There is significant scatter due to age differences, and some of the red galaxies at z=0.2 are blue at 0.5, and are therefor not included in the sample at z=0.5.

2.1. COMPLEX FORMATION HISTORY

There is no good reason to assume that an individual galaxy consists of a coeval population, nor is there any reason to assume that all galaxies have exactly the same age. As an alternative, we constructed galaxies by assuming that star formation starts at z=4, and remains constant until a burst which consumes 10% of the stellar mass. The burst is assumed to occur randomly between z=0.3 and z=2. The galaxy will not be recognized as a early type galaxy until 1.5 Gyrs after the burst. Fig. 1b shows the evolution of the L/M ratios as a function of redshift. There is a spread of about 10% at low redshifts, which increases towards higher redshifts. The mean luminosity evolution is very fast until z=0.2, but then is slows down significantly. This is because galaxies are being lost from the "early type" sample, because they are still blue, or are still undergoing star formation. As a result the set of red, early type galaxies in clusters at larger redshift is not the same as the set of red, early type galaxies in nearby clusters. Especially the younger galaxies in nearby clusters will have been lost. At larger look back times, one selects galaxies which are preferentially older. Similarly, if clusters form at a range of redshifts, then the set of clusters at low redshifts is not necessarily the same as the set of clusters at high redshifts. Caution is therefore needed in the interpretation of the results.

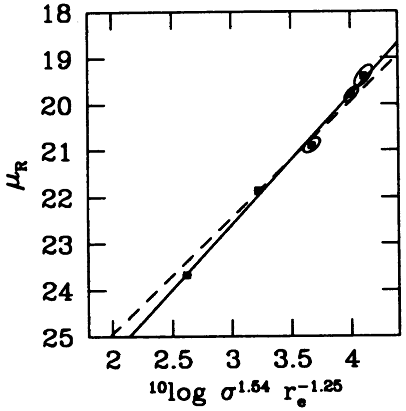

Figure 2. The Fundamental Plane for Abell 665 at z=0.18 . There is a very clear relation, which is very similar to the relation for nearby clusters (dashed line). The scatter is dominated by measurement errors.

3. Application to Abell 665 at z=0.18

It has become possible to measure velocity dispersions of galaxies with redshifts between 0.2 and 0.4 at 4m class telescopes. Typical integration times are 8 hours, or longer. Velocity dispersion of galaxies in Abell 665 at z=0.18 were measured by Franx (1993). These were obtained in a 9 hour integration at the MMT. The central dispersions within a square aperture of 1.8 arcsec were measured, and they were converted to a 'standard' aperture size at the redshift of Coma. The prescription of Jørgensen *et al.* (1995) was followed.

The photometric parameters were determined from images taken at Whipple Observatory, with the 48inch telescope, and with the 2.1m telescope at KPNO. The galaxy images were fitted with the point spread function convolved with an $r^{1/4}$ law. The center, scale length, surface brightness, position angle and ellipticity for each galaxy was allowed to vary. Because the PSF is very well known from the stars, the fit is robust. The least square fitting program produces direct error estimates, and the correlation between the parameters. Not surprisingly, the surface brightness and effective radius are strongly coupled. A similar result holds for determinations of these parameters of nearby galaxies (e.g., Jørgensen *et al.*, 1993). For both the high redshift galaxies, and the low redshift galaxies, the correlation is almost parallel along the relation $r_e \mu_e^{0.8}$, which enters the Fundamental Plane. Hence this combination can be determined in a robust way from the ground based data.

The first result is shown in Fig. 2. The surface brightness is plotted against the combination $\sigma^{1.54} r_e^{-1.25}$. There is a clear relation, and a line with the slope of the relation for Coma is drawn through the points. Clearly,

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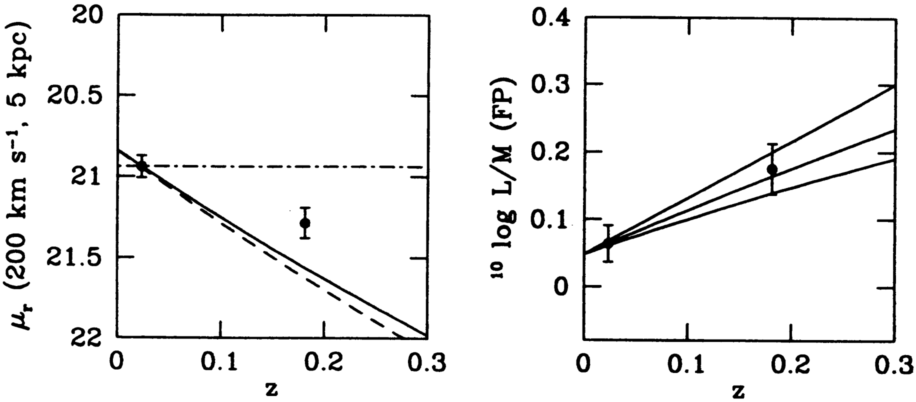

Figure 3. (a) The evolution of surface brightness as a function of redshift. The surface brightness is the surface brightness derived from the Fundamental Plane for galaxies with r_e =5kpc and σ = 200 km/s. The two data points are the R band zeropoint for Coma and Abell 665. The surface brightness decreases with redshift, which is caused by the cosmological surface brightness dimming. The drawn and dashed line show the predicted effect from surface brightness dimming for $q_0 = 1/2$ and 0, respectively. The points lie above the line due to luminosity evolution. (b) The L/M ratio as a function of redshift. The L/M ratio increases with look back time. The curves are model predictions for co-eval populations with $z_{form} = 1, 2, 100$ (from top to bottom), under the assumption that $q_0 = 1/2$. The data are consistent with $z_{form} > 1$.

the relation is very similar at z=0.18 compared to low redshift.

The relation of Fig. 2 was used to determine the zeropoint surface brightness, which was defined as the surface brightness for a galaxy with an effective scale length of 3 kpc, and a velocity dispersion of 200 km/s. This was done for Coma, and Abell 665. The data from Jørgensen *et al.* (1993) were used for Coma, these are the only currently available data in the red for nearby clusters. The result is shown in Fig. 3a. As expected, the surface brightness goes down with redshift - this is due to the cosmological surface brightness dimming. This is the first application of the surface brightness test with the Fundamental Plane, as suggested by Kjægaard *et al.* (1993). It is not quite the same as the 'true' surface brightness test suggested by Tolman (Tolman and Hubble, 1936), because it uses a surface brightness defined at some physical scale length; but the predicted line is not very dependent on the value of q_0. This surface brightness test is complementary to the results of COBE (Mather *et al.*, 1994), which showed that the Cosmic Background Radiation satisfies a Planck curve to within 0.03 %. This imposes a very strong constraint on the evolution of surface brightness with redshift. If the surface brightness were not proportional to $(1 + z)^{-4}$, then the CBR would satisfy such a Planck curve for a very short time (less than 10^6 yr), and we would be living at a very special epoch. It must therefore be considered to be a much stronger test than the result based on

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the Fundamental Plane of galaxies. It is notable that the galaxies of Abell 665 lie significantly above the relation expected for galaxies with constant surface brightness.

After correction of the surface brightness dimming, we can evaluate the evolution of the L/M ratio of the early type galaxies with time. Fig. 3b shows the result for Coma and Abell 665. The increase in L/M can be approximated by $L/M \propto (1+z)^{1.8\pm0.7}$. This is consistent with formation redshifts higher than 1. The results depend on the assumed value of q_0, and the assumption that all cluster galaxies have the same formation redshift.

4. Discussion

The evolution of the M/L can be measured directly from observations of the Fundamental Plane as a function of redshift. The evolution depends strongly on the formation redshift, and can be faster then earlier predictions by Tinsley (1972,1980).

First measurements of cluster galaxies in Abell 665 at z=0.18 indicate that the Fundamental Plane is quite similar in this cluster. The evolution of the zeropoint is consistent with a formation redshift higher than 1.

Further measurements are now needed. It is important to extend these observations to galaxies at higher redshift. Furthermore, it is necessary to test the assumption that all cluster galaxies have had the same star formation history by observing more clusters at low redshift.

References

Buzzoni, A., 1989, *Ap. J. Suppl.* **71**, 817
Djorgovski, S. and Davis, M., 1987, *Ap. J.* **313**, 59
Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R. J. and Wegner, G., 1987, *Ap. J.* **313**, 42
Faber, S. M., Dressler, A., Davies, R. L., Burstein, D., Lynden-Bell, D., Terlevich, R. J. and Wegner, G., 1987, *Nearly Normal Galaxies*, ed. S. M. Faber, New York: Springer, p. 175
Franx, M., 1993, *Ap. J.* **407**, L5
Franx, M., 1995, in preparation
Jørgensen, I., Franx, M. and Kjærgaard, P., 1993, *Ap. J.* **411**, 34
Jørgensen, I., Franx, M. and Kjærgaard, P., 1995, *M. N. R. A. S.*, submitted
Kjærgaard, P., Jørgensen, I. and Moles, M., 1993, *Ap. J.* **418**, 617
Mather, J. C. *et al.*, 1994, *Ap. J.* **420**, 439
Peebles, P. J. E., 1993, *Principles of Physical Cosmology*, Princeton, Princeton University Press
Renzini, A. and Ciotti, L., 1993, *Ap. J.* **416**, L49
Tinsley, B. M., 1972, *Ap. J.* **173**, L93
Tinsley, B. M., 1980, *Fund. Cosmic Phys.* **5**, 287
Tolman, and Hubble, E., 1936,
Worthey, G., 1994, *Ap. J. Suppl.*, in press