Luminous Cluster Ellipticals as Cosmological Standard Rods?

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We explore the possibility to calibrate massive cluster ellipticals as cosmological standard rods. The method is based on the Fundamental Plane relation combined with a correction for luminosity evolution which is derived from the Mg−σ relation. Principle caveats and sources of major errors are briefly discussed.

We apply the described procedure to nine elliptical galaxies in two clusters at \( z = 0.375 \) and derive constraints on the cosmological model. For the best fitting \( \Lambda \)-free cosmological model we obtain: \( q_0 \approx 0.1 \), with 90\% confidence limits being \( 0 < q_0 < 0.7 \) (the lower limit being due to the presence of matter in the Universe). If the inflationary scenario applies (i.e., space has flat geometry), then, for the best fitting model, matter and \( \Lambda \) contribute about equally to the critical cosmic density (i.e. \( \Omega_m \approx \Omega_\Lambda \approx 0.5 \)). With 90\% confidence \( \Omega_\Lambda \) should be smaller than 0.9.

A more detailed account of the work presented here has recently been published.

1 Formation and evolution of elliptical galaxies

Kinematical studies of nearby massive elliptical galaxies have shown that most of these objects have experienced a complex formation history. Especially kinematically decoupled cores are indicative of violent similar–mass mergers. While the formation of field ellipticals may continue until today \( z \approx 0.5 \), cluster ellipticals must have undergone their major merging period at redshifts \( z > 0.5 \) or even \( z > 1 \). This follows on the one hand from the homogenous properties of local cluster ellipticals and, on the other hand, from the very small redshift evolution of their luminosities, colors and spectral indices. Furthermore, the redshift evolution of the Fundamental Plane (FP) relation of cluster ellipticals has been found to be consistent with purely passive evolution of their stellar populations.

Passive evolution of cluster ellipticals up to redshifts of 0.5 to 1 (depending on the cosmological model) is also consistent with hierarchical galaxy formation models. Even in the standard \( \Omega_o = 1 \) cold-dark-matter model (with strong low redshift evolution), neither significant star formation nor accretion processes take place in cluster ellipticals at \( z < 0.5 \). The star formation activity observed in cluster galaxies at modest redshifts seems to be confined to blue infalling and/or harrassed disk galaxies which may turn into intermediate luminosity S0s today but are unlikely to alter the population of massive cluster ellipticals at a significant level.
2 The method

Our method to calibrate massive cluster ellipticals as cosmological standard rods relies on the Fundamental Plane (FP) relation combined with a correction for luminosity evolution. The latter is based on the distance-independent Mg-σ relation and the assumption that cluster ellipticals evolve passively.

The FP describes the observed tight scaling relation between effective radius \( R_e \), mean effective surface brightness \( \langle SB \rangle_e \) and velocity dispersion \( \sigma \) of cluster ellipticals: 
\[
\log R_e = 1.25 \log \sigma + 0.32 \langle SB \rangle_e - 8.895 \quad \text{with} \quad R_e \text{ in kpc, } \sigma \text{ in km/s, } \langle SB \rangle_e \text{ in the B-band.}
\]
The constant -8.895 was derived from the Coma cluster ellipticals with a Hubble constant of \( H_0 = 50 \text{km/s/Mpc} \), the error in the constant is about 0.01. The FP allows to predict the effective radii \( R_e \) of elliptical galaxies with better than 15% accuracy from their velocity dispersions and surface brightnesses, i.e., a distance dependent quantity \( R_e \) can be estimated from two distance independent quantities \( \langle \sigma, \langle SB \rangle_e \rangle \). If a large enough number of ellipticals are measured per cluster then the distance to the corresponding cluster can be determined with an accuracy better than 5%.

As argued in the previous section, we have strong evidence that massive ellipticals in rich clusters evolve only passively between now and at least \( z \approx 0.5 \). Passive evolution of the stellar population can be accurately measured with the Mg-σ relation which is independent of \( q_0 \) and \( H_0 \), and is within current uncertainties the same for clusters of similar richness/velocity dispersion. In local cluster ellipticals, the Mg\(_b\) absorption is tightly coupled to the velocity dispersion \( \sigma \) of the galaxy. Together with the Fundamental Plane this constrains the scatter in age and metallicity at a given \( \sigma \) to be smaller than 15%. Therefore, in the case of passive evolution, Mg\(_b\) decreases with redshift only because the age of the population decreases. One can use population synthesis models to translate the observed Mg\(_b\) weakening into an estimate of the B-band luminosity evolution. Based on recent models we obtain consistently \( \Delta B = 1.4 \Delta \text{Mg\(_b\)} \) for a Salpeter initial mass function, metallicities between 1/3 and 3 times solar and ages between 3 Gyr and 15 Gyr. The slope of 1.4 shows no dependence (within 0.1) on evolutionary tracks and other differences in the synthesis models, which demonstrates that this differential comparison of Mg\(_b\) and B-band evolution is quite robust.

3 Results from a first application

As a first application of the method we observed nine elliptical galaxies in two clusters at a redshift of \( z = 0.375 \). We used the Hubble Space Telescope to derive effective radii \( R_e \) and surface brightnesses \( \langle SB_e \rangle \) and the Calar Alto
3.5m telescope to obtain velocity dispersions \( \sigma \) and Mg\(_b\)-indices. Additional photometric calibrations were obtained with the ESO NTT and the Calar Alto 2.2m telescope. The reduction procedures are described in more detail in [26, 24].

The surface brightness of the \( z = 0.375 \) ellipticals was transformed to rest-frame B-band, corrected for cosmological dimming \(((1 + z)^4)\) and for passive evolution using the Mg\(_b\) – \( \sigma \) relation described above. For the local comparison sample we used elliptical and S0 galaxies in the Coma cluster.

Figure 1 (bottom) shows the edge-on view of the Fundamental Plane for Coma ellipticals (with \( \sigma > 120\text{km/s} \)) and for the \( z = 0.375 \) ellipticals. The angular distances at which a perfect match between the two samples is achieved are 139 Mpc/\( h_{50} \) for Coma and 1400 Mpc/\( h_{50} \) for the \( z = 0.375 \) ellipticals (\( h_{50} \) is the Hubble constant in units of 50km/s/Mpc). The luminosity correction is calculated based on the mean offset in the Mg\(_b\) absorption of the local and the \( z = 0.375 \) sample, i.e., \( \Delta(SB)_{B,e} = 1.4\Delta M_{Mg_b} = 0.48 \text{mag/arcsec}^2 \). We could also have corrected the luminosity evolution of the objects individually and would have obtained the same result. In fact, the residuals of the distant ellipticals from the Fundamental Plane and from the Mg\(_b\) – \( \sigma \) relation do indeed correlate with each other in the expected way, though the error bars are large (Figure 1 top). This supports the idea that the evolution we see is really due to age (and not metallicity). While for local samples of ellipticals we cannot conclude reliably that the residuals from the FP and Mg\(_b\) – \( \sigma \) relations are correlated and caused by age [16], the effects of age spread must increase with redshift and may lead to the observed correlation in the residuals.

The cosmological model is constrained on the basis of Figure 1 as follows. The distance ratio at which the fully corrected FP of the \( z = 0.375 \) clusters Abell 370 and MS1512+36 matches the FP of the Coma cluster is \( 10.1 \pm 0.8 \). With an angular distance of 139 Mpc/\( h_{50} \) to the Coma cluster (corrected to the Cosmic Microwave Background rest-frame [4]), this ratio corresponds to an angular distance of 1400 Mpc/\( h_{50} \) to the \( z = 0.375 \) clusters. For a plausible range of cosmological models, the distance to the Coma cluster is, because of its proximity, virtually independent from \( q_0 \) (at the level of 0.5%), while the distance to the \( z = 0.375 \) clusters varies by more than 10%. Since the geometry of the Universe is determined by the ratio of distances, \( q_0 \) is independent of the Hubble constant. The relative error of mean distance to the \( z = 0.375 \) clusters is about 8%. The mean distance to \( z = 0.375 \) and its error give immediate constraints on the cosmological model (see Figure 2). If the cosmological constant vanishes then our measurements, together with the observational fact that there exists matter in the Universe, constrain the cosmological density parameter to be \( 0 < \Omega_m < 1.4 \), or the cosmological deceleration parameter to be \( 0 < q_0 < 0.7 \), with 90% confidence. The best fit
Figure 1: Lower panel: The Fundamental Planes of Coma cluster ellipticals and evolution-corrected cluster ellipticals at \( z = 0.375 \) in rest frame B-band. The angular distance to \( z = 0.375 \) is derived as 1400 Mpc/\( h_{50} \) if Coma is at 139 Mpc/\( h_{50} \) distance (\( h_{50} = H_0/(50 \text{ km/s/Mpc}) \)). The upper and lower dashed lines show the FP relations of the \( z = 0.375 \) objects if their distance were 1100 Mpc/\( h_{50} \) and 1700 Mpc/\( h_{50} \), respectively. Upper panel: The Mg indices of the \( z = 0.375 \) ellipticals relative to the Mg-\( \sigma \) relation of Coma Es. The luminosity evolution of the \( z = 0.375 \) Es was derived and corrected using the mean offset of the Mg values.

Figure 2: The plane of matter density vs. cosmological constant. Matter density is given by \( \Omega_m \), the cosmological constant is represented by \( \Omega_\Lambda = \Lambda/(3H^2) \). Lines of constant angular distance for a redshift of 0.375 are shown. The ellipticals observed at this redshift (Figure 1) allow to constrain the angular distance to \( z = 0.375 \) which in turn defines a probability strip in the \( \Omega_\Lambda - \Omega_m \) plane. Values for \( \Omega_\Lambda \) and \( \Omega_m \) which have > 90% likelihood lie in the shaded area. The horizontal long-dashed line corresponds to a Universe without a cosmological constant, the diagonal short-dashed line to a Universe with no curvature (\( \Omega_m + \Omega_\Lambda = 1 \)).
suggests $q_0 = 0.1$. If the Universe has flat geometry as suggested by inflation, then the preferred model would have $\Omega_m = \Omega_\Lambda = 0.5$. $\Omega_\Lambda$ is constrained to fall in the range $-0.25 < \Omega_\Lambda < +0.9$, again with 90% confidence.

**Caveats.** To conclude we address some caveats of the proposed method which can be studied and checked more thoroughly once large samples of distant ellipticals become available:

1. Dynamical evolution could alter the Fundamental Plane relation. However, at present objects of very different dynamical structure (S0s, rotationally flattened and anisotropic Es) all lie on the same FP indicating that it is robust against changes in dynamical structure.

2. Environmental dependences of Fundamental Plane and $\text{Mg} - \sigma$ relations. So far no significant dependences have been found for clusters of similar richness. Moreover, if the FP varied by even a few percent, peculiar velocities of clusters could not be derived.

3. We estimated the combined biasing effect of the sample size, sample selection and allowed range of the FP parameters by means of Monte Carlo simulations. We find that the systematic bias of the FP zero-point is still smaller than the random variation due to sample size.

4. Significant dust absorption can be ruled out, because it would cause a $(B - V) - \text{Mg_b}$ relation at $z = 0.375$ offset from the local one, which we did not find.

5. Differential relation between $\text{Mg}_b$ weakening and $B$-band evolution. We checked various models and found no significant difference, even for models with different evolutionary tracks. The major uncertainty is whether all ellipticals have a stellar initial mass function with Salpeter slope for masses around and below the solar mass (for a more detailed discussion see).

6. Influence of mixed populations. We performed tests with varying fractions of intermediate age populations, all constrained in a way that the objects at $z = 0.375$ would not be regarded as of $E + A$ type from spectral characteristics. For plausible population mixes, the uncertainty in the evolution correction is significantly smaller than 0.1 mag.

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