TESTING THE WORLD MODEL THROUGH HIGH REDSHIFT GALAXIES IN CLUSTER

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ABSTRACT. We discuss the results of a cosmological test involving mean colors of the early-type galaxy population in distant clusters for tracing the World model. A global approach to the cosmological problem is attempted deriving the allowed combinations for the fundamental parameters (H_o, q_o, λ_o), and the redshift of galaxy formation (z_f).

1. Introduction

It is well known that a measure of the geometry of the Universe is the most direct and safe way to determine its curvature. However, when attempting a test resting on galaxies as standard candles, as the classical case of the Hubble diagram for example, the main set-back is that the evolution of the reference objects at high redshift could play a crucial role modulating our inferences about the cosmological model (Sandage 1988; Yoshii & Takahara 1988).

On the other hand, by learning how galaxies are and evolve we would get a powerful tool to estimate the geometry of the space. This can be done via stellar evolution applied to the study of the galactic stellar populations. So far, stellar evolution stands on solid grounds and we master in great detail the nuclear clock of stars. This will provide a safe link between the look-back time and the redshift allowing thus to determine which cosmological parameters fit better the observations.

Our approach to the cosmological problem is based on the observation and theoretical determination of the colors of cluster elliptical galaxies. Compared to magnitudes, colors are less dependent on aperture corrections and their direct determination does not depend on the distance. A relevant advantage comes then from considering elliptical galaxies, respect for instance to spirals, as to a large extent their evolutionary history is under control. Interstellar gas in ellipticals is scarce, and this suggests an extensive star formation which should have occurred early in the lifetime of the galaxies. It is a plausible working hypothesis, therefore, to consider their stellar populations as coeval with their age coinciding with that of the parent galaxy.

Finally, a last advantage using cluster galaxies as a set of objects located at the same distance is that due to a more favourable statistics, we can deduce the mean photometric properties of the whole sample with a larger confidence respect to single field objects.

2. The Observational Data Base

Seven clusters with redshift ranging from $z = 0.15$ up to 0.58 have been accounted for in our test. They are part of an ongoing observing programme undertaken by our group since 1986 at the ESO telescopes in La Sill. (Chile). More extended details about the observations (taken in the Gunn g, r, i photometric system) and data reduction (using ESO MIDAS package) can be found in the contribution by Molinari *et al.* (this congress) where we present the results for three of the relevant clusters, and in Molinari, Buzzoni & Chincarini (1990) for a more general discussion of the procedures involved.

In the following calculations, mean colors for the population of elliptical galaxies in each cluster have been corrected for Galactic extinction according to Burstein & Heiles (1982) adopting $E(g-r) = 1.10E(B-V)$ and $E(g-i) = 1.73E(B-V)$.

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3. Matching Theory and Observations

Although we cannot directly estimate the morphology of the galaxies in our distant clusters, it is reasonable however to identify ellipticals by means of their colors. As we showed in Molinari *et al.* (this congress) a majoritary population of galaxies systematically appears in the $(g-r)/(g-i)$ diagrams of the clusters clearly segregating as a clump of red objects. Moreover, the location of the red clump smoothly moves redward with increasing redshift and can be tracked quite confidently by evolving back in time present-day ellipticals. Therefore, this leads us to conclude that such red galaxies are indeed *bona fide* progenitors of present-day ellipticals. Based on Buzzoni's (1989) models for population synthesis, Molinari, Buzzoni & Chincarini (1990) derived the expected reference colors of redshifted early-type galaxies both for "passive" and "active" evolution (see quoted reference for further details).

Before proceeding on with our analysis, it is essential to clarify a preliminary question, possibly relevant for our aims, dealing with a safe determination of the metallicity of the elliptical galaxies. Since age and metallicity affect the galactic colors in the same way (Renzini & Buzzoni 1986) we need to disentangle the two effects in order to properly tune the stellar clock.

On the basis of a calibration of the Mg_2 spectral index, Buzzoni, Gariboldi & Mantegazza (this congress, 1991) studied the metallicity distribution for local early-type galaxies deriving typically [Fe/H] $= +0.2$, i.e. a value about 50% higher respect to the solar metallicity. Note that by using a solar [Fe/H] we would predict bluer colors at a given redshift, and consequently an older age for the Universe would be derived from the fit to the data. It is worth remarking that in no relevant way a spread in metallicity among cluster galaxies would affect our test through the well known Visvanathan & Sandage (1977) c-m effect. The net result would be in fact only a spread in the colors without affecting the mean values for the whole galaxy population on which rests in practice our fit.

4. The Cosmological Test

4.1 FRIEDMANN SOLUTIONS WITH $\lambda_o = 0$

In Fig. 1 we display a comparison between data and theoretical reference colors expected for two relevant choices of the deceleration parameter q_o pertinent to a (virtually) empty Universe ($q_o = 0$) and an Einstein–De Sitter model ($q_o = 1/2$). This procedure can be refined searching for the best fitting cosmological models through an iterative alogorithm. For a fixed value of q_o, in the range 0–1, we computed the expected colors for the clusters in our sample with varying H_o in the range 20–100 km/sec/Mpc. Minimization of the color residuals gave then the allowed combination in the (q_o, H_o) domain assuming different values for z_f. The best fits to the observations gave typically an rms of about 0.03 mag. The most direct result in the procedure is that a negative correlation exists between the Hubble constant and the deceleration parameter in the sense that smaller values for q_o require larger values for H_o. Assuming galaxies to be formed at $z_f = \infty$ we derive for the Universe a present age of $t_o = 16 \pm 2$ Gyr. A firm conclusion also deriving from Fig. 1, is that an Einstein–De Sitter model is not supported by the observations.

Accounting for all internal uncertaintes in the fit, an upper limit for the Hubble constant can be set at $H_o \leq 68$ (assuming $q_o = 0$). This is in agreement with the most recent determination of $H_o = 52 \pm 2$ given by Sandage & Tammann (1990), and with their lower limit at 45 ± 3. With $H_o = 52$ and assuming galaxies to have the same age of the Universe we derive $q_o = 0.06^{+0.14}_{-0.06}$ with a safe upper limit at 0.46.

Of course, the epoch of galaxy formation is still an open question widely discussed in the literature (Wyse 1985; Yoshii & Takahara 1988). A lower limit such as $z_f \geq 4$ can be derived from our test assuming for H_o the value by Sandage and Tammann.

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4.2 INFLATIONARY SCENARIOS WITH $\lambda_o \neq 0$

A large amount of work went into solving some of the theoretical problems in the framework of the cosmological inflation theory with $\Omega_o = 1$. On the other hand, none of these attempts fully succeded in reconciling theoretical expectations with observations of the real galaxies (Yoshii & Takahara 1988; Fukugita *et al.* 1990; Guiderdoni & Rocca–Volmerange 1990).

A way out could be either the introduction of number counts evolution at high redshift (Rocca–Volmerange & Guiderdoni 1990) or a non-zero value for the cosmological constant λ_o (Fukugita *et al.* 1990). The latter possibility could be somewhat attractive because it preserves the present status of knowledge about galaxy evolution. In an inflationary scenario with zero–curvature space we have $\Omega_o + \lambda_o = 1$ providing to express the cosmological constant in normalized units such as $\lambda_o = 2/3\Lambda(c/H_o)^2$. A simple relationship links then the deceleration parameter: $q_o = 3/2\ \Omega_o - 1$.

When applying our previous analysis also to this case we have that even for the lower limit of H_o , the cosmological constant must be greater than 0.35 ($\Omega_o \leq 0.65$). For H_o =52 we derive $0.6 \leq \lambda_o \leq 0.85$ which leads to a preferred range of $0.15 \leq \Omega_o \leq 0.4$ for the density parameter. In this framework q_o is negative implying that the Universe scale factor is now increasing with positive acceleration. It is worth noting that our conclusions fully agree with the results of Fukugita *et al.* (1990) based on a completely independent analysis of deep galaxy counts.

As a final remark, we have that a small value for Ω_o would call for a value of H_o larger than 50 and possibly in the range 60-80 km/sec/Mpc. This might reconcile therefore a low-density Universe with a large value for the Hubble constant as it seems to derive for instance from the Tully-Fisher relation (Aaronson *et al.* 1980).

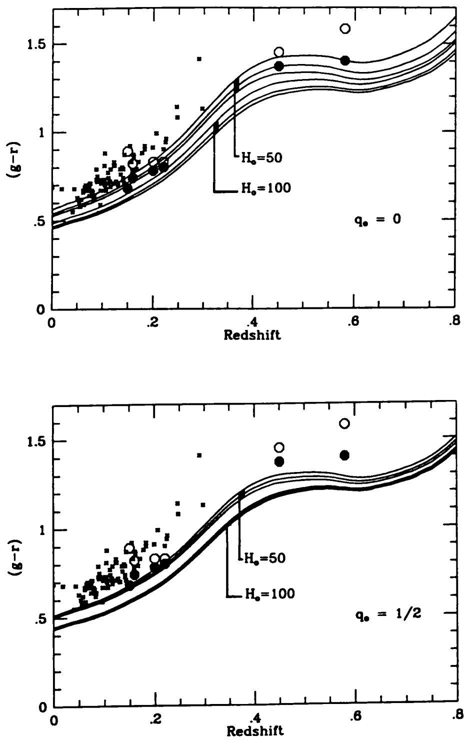

Fig. 1- Comparison between colors for cluster ellipticals in our observational sample and theoretical expectations for relevant cosmological models. In both panels filled dots represent the *mean* colors for ellipticals while open dots mark the colors for the *first-ranked* galaxies in each cluster. For comparison we reported also the observations by Schneider, Gunn & Hoessel (1983) (little crosses) referring only to first-ranked galaxies in their cluster sample. Theoretical color evolution is computed using Buzzoni's (1989) code for population synthesis assuming for galaxies [Fe/H] = +0.2. The two relevant values for the deceleration parameter q_o are displayed in each panel. Two families of curves have been computed according to H_o = 50 and 100 km/sec/Mpc, as labelled in the panels. For each value of H_o we assumed z_f = 3, 5 and ∞ (moving from the bluest to the reddest curve respectively).

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Discussion

Djorgovski: What is, in more detail, the transformation you use to convert the Mg index into $[Fe/H]$?
Buzzoni: I used the calibration proposed in Buzzoni, Gariboldi & Mantegazza (see this congress). Briefly, the dependence of the Mg_2 index on [Fe/H] is $\partial Mg_2/\partial[Fe/H] = 0.135$ with a zero-point such as $Mg_2 = 0.28$ for stellar populations of solar metallicity.

Chokshi: Which colors do you predict for galaxies at $z = 0$, and are they consistent with those really observed?
Buzzoni: Synthetic colors for early-type galaxies at present time are found to be $(g-r) = 0.53\pm0.02$ and $(g-i) = 0.75 \pm 0.03$. To be consistent with our observations, these colors have been computed in the Gunn system as reproduced at ESO. While no difference occurs for the $(g-i)$ color respect to the standard system (in the range pertinent to galaxies), the $(g-r)$ is about 0.04 mag redder. Quite curiously, for what I know there are not extensive works reporting good photometry of local galaxies in the Gunn system. From observations of clusters at low redshift Schneider, Gunn & Hoessel (1983, ApJ, 264, 337) derive $(g-r) = 0.51$ and $(g-i) = 0.78$ (in the restframe and accounting for the little correction quoted above).

Bruzual: How confidently do your evolutionary models fit the first-ranked galaxies in the clusters? It seems to me that your predicted colors are systematically bluer respect to the observations. Is it a problem with the calibration?
Buzzoni: The synthetic models were *not* intended to fit first-ranked galaxies. To be consistent, we should enhance metallicity up to [Fe/H] = +0.5 predicting therefore redder colors. Our aim only was to reproduce the mean population of early-type galaxies on which relies the cosmological test.

Ferguson: To what extent are your constraints on H_o dependent on the match of your models to low-redshift galaxies? In other words: which constraints on H_o , q_o and λ_o do you still have by forcing your evolution models to fit present-day galaxies alone?
Buzzoni: The main conclusion accounting for the photometric properties of the present-day ellipticals converges toward an age about 15 Gyr and an IMF consistent with the Salpeter law. This is therefore fully consistent with the conclusions of the present work confirming that we are tracking confidently the history of the galaxies from $z = 0$ back in time.