THE ASTROPHYSICAL JOURNAL, 410:499–506, 1993 June 20

GALAXY COLORS IN DISTANT CLUSTERS AS A TEST FOR THE WORLD MODEL[1]

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Received 1992 February 13; accepted 1992 December 7

ABSTRACT

Colors of elliptical galaxies in nine distant clusters ($z \leq 0.5$) are studied with reference to theoretical models for evolutionary population synthesis (Buzzoni 1989) inferring allowed ranges for the relevant cosmological parameters.

Galaxies at $z = 0.2$ are found to be coeval within ± 3 Gyr and consistent with an absolute age of 12 Gyr. The look-back time from $z = 0.2$ to $z = 0.45$ is not larger than 4 Gyr. In a Fiedmann cosmology this leads to a current age of the universe of 16 ± 2 Gyr and an upper limit to the Hubble constant of 68 km s^{-1} Mpc^{-1}. The value of $H_0 = 52 \pm 2$ recently suggested by Sandage and Tammann is supported by the data. In this case the deceleration parameter is found to be $q_0 = 0.06^{+0.14}_{-0.06}$. We also find marginal evidence for galaxies to form at redshift $z_f > 5$.

The Einstein-de Sitter model is not supported by observations if $\Lambda_0 = 0$ unless we accept an exceedingly low value for $H_0 \leq 41$ km s^{-1} Mpc^{-1}. A zero-curvature space would rather demand $\lambda_0 > 0.35$ [$\lambda_0 = 1/3\Lambda_0(c/H_0)^2$] with a preferred range $0.6 \leq \lambda_0 \leq 0.85$. Accordingly, the density parameter Ω_0 should range between 0.15 and 0.4 with an upper limit about 0.65.

Subject headings: cosmology: observations — distance scale — galaxies: clustering — galaxies: photometry

1. INTRODUCTION

Once a model universe has been selected the relationship between redshift and time is univocally determined. Therefore, either quantity could be suitable in principle for cosmological tests. The Hubble diagram is probably the most classical tool to estimate the relevant cosmological parameters since at low redshift it constrains the Hubble constant (H_0), whereas at high redshift the correlation between distance and redshift increasingly depends on the deceleration parameter q_0. The total mass inferred from the cosmological deceleration could be then compared with the direct measure of the matter content through the density parameter Ω_0 to estimate eventually the possible value of the cosmological constant Λ_0.

All this is somehow far from the real world of the data, however. A reliable distance ladder is in fact the big problem in observational cosmology. Even assuming that a fair standard candle might exist at low z, by probing the universe at large distances we fatally deal with galaxies that emitted their light at a look-back time comparable with the evolutionary time scale of their stars. To properly account for the expected changes in the intrinsic properties of the reference objects we would need therefore a complete knowledge of the evolutionary mechanisms at work. It is such a difficulty, for instance, that has prevented so far a confident estimate of q_0 through the Hubble diagram (see, for example, Lebofsky 1978; Sandage 1988), and also deep galaxy counts suffer in principle from the same problems (Loh & Spillar 1986; Yoshii & Takahara 1988; Guiderdoni & Rocca-Volmerange 1990).

Stellar evolution acts with respect to z in a way equivalent to a distance ladder relating cosmological redshift with look-back time. In practice, if we can predict how colors of galaxies change with time and observe how they change with redshift we can link the cosmological space time.

This approach is not a new one. A number of works in this direction have been carried out by Kristian, Sandage, & Westphal (1978), Lilly & Longair (1984), Hamilton (1985), Dunlop et al. (1989), among others. We believe nevertheless that the present work allows a step forward not only due to the additional data which have become available but also because this new analysis rests on the colors of elliptical galaxies in clusters and on rather improved evolutionary models.

The operational advantage of using colors of galaxies rather than magnitudes is that colors are much less sensitive to q_0-dependent aperture corrections in the photometry, and their estimate is not strongly influenced by the distance as is the case for the apparent magnitudes. Moreover, considering galactic evolution, it is known that colors are less dependent than magnitudes on the initial stellar mass function, allowing a less critical match with the models of population synthesis (Tinsley 1972; Searle, Sargent, & Bagnuolo 1973; Buzzoni 1989).

A further advantage of looking at elliptical galaxies is that we can reach larger distances since they are among the brightest cluster members (Binggeli, Sandage, & Tammann 1988), and their evolutionary path is much better understood than that, for instance, of late-type spirals. Lack or scarcity of interstellar gas introduces negligible corrections for internal reddening in these galaxies and makes plausible the hypothesis that star formation mainly took place during one single event that occurred in the early stages of the life of galaxies. As a consequence, we have to expect that the age of the elliptical galaxies coincides with that of their stellar populations. Finally, looking at clusters we include a larger population of galaxies all at the same distance allowing us to measure the mean photometric properties of the sample with higher statistical significance with respect to single objects.

The data we used in our analysis are presented in § 2, while in § 3 we discuss some relevant warnings in order to match data with appropriate models for evolutionary population synthesis. Dating elliptical galaxies and overall cosmological implications of our test will be analyzed in § 4 where we also derive constraints to the cosmological parameters. We con-

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sider in this section also the case of inflationary scenarios with a nonzero cosmological constant. Finally, our conclusions are summarized in § 5.

2. THE DATA

In 1986 we started a long-term project aimed at studying the galaxy population in distant clusters. Observations were carried out mainly with the ESO 3.6 m telescope at La Silla, Chile. CCD imaging was performed using EFOSC at the Cassegrain focus (Buzzoni et al. 1988; Molinari, Buzzoni, & Chincarini 1990; Molinari et al. 1992a, b, c).

Clusters have been selected from the revised ACO catalog (Abell, Corwin, & Olowin 1989) among those most distant and still visible on the photographic prints of the ESO UK Southern Survey, and from the deep surveys published by Gunn, Hoessel, & Oke (1986), and West & Frandsen (1981). All the observations were made in the g, r, i Gunn system available at ESO (Sinclaire 1987; Melnick, Dekker, & D'Odorico 1989).

Data reduction has been performed using the MIDAS package (see MIDAS Users Guide, Image Processing Group, ESO V4.3, 1988). For each cluster, a total of 50 minutes integration time per color was typically obtained by stacking up three/four frames to erase cosmic rays and spurious features. Search for galaxies and systematic photometry was accomplished on the stacked images using the package INVENTORY (West & Kruszewski 1981) as implemented in MIDAS. Objects of mag 22 can be confidently detected and located on the frames at $S/N > 50$ while the faintest galaxies still visible are about $r \sim 24$. A good completeness level in the detection algorithm was achieved about 1 mag brighter. Isophotal magnitudes were computed at the 1% level of the local sky background while colors were derived over a 3″–4″ circular aperture, slightly wider than the seeing disk in order to collect most of the light of the objects.

The internal accuracy in the magnitude estimates has been found to be about 0.15–0.20 mag at $r \sim 22$. Careful standard star calibration allowed us to reproduce the photometric system throughout the different observing runs within 0.05–0.10 mag. As discussed in Molinari et al. (1990), there are few differences in the ESO Gunn system with respect to the canonical system. A direct test by convolving numerically the g, r, i filter responses as given in Thuan & Gunn (1976) and Schneider, Gunn, & Hoessel (1983) with some spectral templates for red stars and galaxies allowed us to conclude that while the $g - i$ is essentially the same, the $g - r$ of ESO is about 0.04 mag redder. Special care has to be paid, therefore, to consistently match observations and reference synthetic colors as we will discuss in § 4.

In order to increase the data base, we included in our analysis also data for three clusters in the same relevant range of distance observed by Garilli, Maccagni, & Vettolani (1991) and Garilli et al. (1992) (a further cluster observed by Garilli et al. 1992, MSS 0043−25, was not considered as it was not possible to define the mean colors of ellipticals confidently). Those observations were carried out at ESO using a fully consistent photometric system (i.e., the same CCD detector and same Gunn filters as in our observations). The only difference is that standards were defined as in the Pedersen (1988) calibration, and a transformation is needed to our system. On the basis of the list of the eight primary standards in common with Pedersen and Gunn we adopted the following transformations: $(g - r)_{\rm ESO} = 1.171(g - r)_{\rm Ped} - 0.533$ and $(g - i)_{\rm Ped} + 0.312(g - r)_{\rm Ped} - 0.822$ (M. Banzi 1991, private communication), with a typical uncertainty of ± 0.03 mag in the transformed colors. As can be seen, there is a nonnegligible color term to be accounted for in the transformations affecting especially $g - r$. As a consequence, a too rough match to the standard system is given by adopting the simplified relation suggested by Garilli et al. (1991). In addition, we note that the transformations are defined for stars bluer than $(g - r)_{\rm ESO} \sim 0.6$ or $(g - i)_{\rm ESO} \sim 0.8$ so that we are in mild extrapolation matching the two clusters A3186 and A3639 while an even larger uncertainty might affect the color transformation of S0400.

Unfortunately, the lack of a proper definition of the color equation prevented us from including in our analysis also the data of Dressler & Gunn (1992) on seven clusters beyond $z = 0.35$. Their apparent colors are in fact systematically too red (up to 0.1–0.2 mag) than our photometry at similar redshift both in $g - r$ and $g - i$. This might be induced by a slightly different g magnitude scale that maximizes differences between the Gunn system as defined in photoelectric and CCD photometry. It is well recognized that this could be a problem when observing high-redshift galaxies (see Schneider et al. [1983] for a detailed discussion). It is fair to note however that the effect still preserves a perfect agreement between the combined $(g - r)/(g - i)$ colors of our clusters and the composite color-color relation $(g - i) = 1.4(g - r) - 0.03$ given by Dressler & Gunn (1992) for their seven clusters (see their Fig. 12).

In the $(g - r)/(g - i)$ color diagrams of the cluster fields the population of bona fide early-type galaxies clearly appears as a prominent clump of red objects moving to redder colors with increasing redshift (Molinari et al. 1990; Molinari et al. 1992a, see their Fig. 1). Although at large distances we cannot directly discriminate the morphological type of the galaxies, the inspection of red objects in the clump of low-redshift clusters as well as selected spectroscopy in more distant clusters seems to support the validity of our assumption (see also, for example, Luppino et al. 1991; Pickles & van der Kruit 1991; Dressler & Gunn 1992).

Operationally, the mean colors of the early-type galaxy population have been obtained starting from the $(g - r)/(g - i)$ diagram. A Gaussian fit of the whole galaxy distribution in the red clump has been computed in the color phase space including all objects within a radius of 0.2 mag around the peak in both colors. Field galaxies do not affect the procedure since we are dealing with overcounts in the two-color diagram and not with the spatial distribution of the galaxies. The only constraint to the sample was therefore the complete g, r, i photometry. It is unlikely, in our opinion, that these selection criteria could have introduced appreciable bias in our computations, and adopted values for the mean colors can be confirmed also by considering the $g - r$ and $g - i$ distributions separately.

A little complication could arise in principle due the fact that cluster photometry is limited in apparent magnitude, and the galaxy population in the most distant clusters is therefore sampled at brighter absolute magnitudes. Due to the color-magnitude relation (Visvanathan & Sandage 1977), the apparent $g - r$ of cluster ellipticals becomes about 0.1 mag redder per r magnitude interval, increasing galactic luminosity (Dressler & Gunn 1992). As a consequence, the clump of galaxies in the two-color diagram could be biased toward slightly redder colors with increasing redshift. However, the difference in the limiting absolute magnitude between low-redshift and more distant clusters in our data base does not exceed 1 mag, and we are confident therefore that the next effect on the

TABLE 1

RELEVANT PROPERTIES OF THE CLUSTERS

Name	l	b	z	$(g-r)_{\rm ell}$ / $(g-r)_1$	$(g-i)_{\rm ell}$ / $(g-i)_1$	E_{B-V}	R_c	N_T	$N_{\rm ell}$	$T_{\rm BM}$	References
A3186	288.6	−37.6	0.127	0.71	1.13	0.04	0.16	95	39	I–II	1
				0.81	1.25						
A3284	250.3	−41.2	0.150	0.68	1.04	0.00	0.24	146	69	I	2
				0.89	...						
A3639	346.9	−26.3	0.149	0.70	1.04	0.04	...	...	52	I	3
				0.73	1.12						
A3305	242.5	−36.9	0.157	0.74	1.02	0.00	0.20	129	51	I–II	2
				0.82	1.01						
Cl 1141−283b	286.9	31.9	0.21	0.88	1.24	0.09	...	...	15	...	4
				0.93	1.32						
A1942	355.4	54.8	0.224	0.82	1.09	0.02	0.24	130	64	III	2
				0.85	1.13						
S0400	238.4	−50.2	0.318	1.23	1.62	0.00	0.31	140	59	II:	1
				1.43	1.93						
Cl 2158+0351	63.7	−38.3	0.445	1.41	1.76	0.04	0.25	160	28	I–II	5
				1.49	1.82						
Cl 1141−283a	286.9	31.9	0.50	1.50	2.04	0.09	...	...	45	...	4
				1.68	2.16						

REFERENCES.—(1) Garilli et al. 1992; (2) Molinari et al. 1992b; (3) Garilli, Maccagni, & Vettolani 1991; (4) this work; (5) Molinari, Buzzoni, & Chincarini (1990).

derived mean colors should be well less than a 0.1 mag excess. Furthermore, we have to recall that the position of the clump in the two-color distribution is weakly sensitive to the cutoff magnitude as in any case it is mainly tracked by the brightest galaxies, thanks to their lower photometric errors.

The relevant parameters of the whole set of clusters have been listed in Table 1. In the table, identifications are taken from the ACO catalog except Cl 2158+0351 which comes from the list of Gunn et al. (1986), and Cl 1141−283 which has been discovered by West & Frandsen (1981). From our unpublished spectroscopy this cluster appears as a double structure with a loose clump of galaxies in the foreground at $z = 0.21$ superposed to a distant cluster at $z = 0.50$ (this value is slightly different from that of West & Frandsen [1981] who gave $z = 0.58$). Accordingly, the two groups are considered separately in the table. The other quantities displayed in Table 1 are in the order Galactocentric coordinates (l, b), adopted redshift, mean observed colors (i.e., not reddening-corrected) both for the whole population of ellipticals [$(g-r)_{\rm ell}$ and $(g-i)_{\rm ell}$] and for the first-ranked galaxies [$(g-r)_1$, and $(g-i)_1$], and adopted color excess from Burstein & Heiles (1982). Where possible, we derived the core radius R_c (in Mpc) and the total number of member galaxies N_T by fitting each cluster spatial distribution with a King profile, assuming $(H_0, q_0) = (50$ km s^{-1} Mpc^{-1}, 0). The total number of fiducial elliptical galaxies considered to calculate the mean color ($N_{\rm ell}$) is also reported. Finally, the Bautz-Morgan type follows ($T_{\rm BM}$) and the reference source of the photometry.

Considering that the error bar on the mean colors of elliptical galaxies scales at least as $(N_{\rm ell})^{1/2}$, we estimate that the internal statistical uncertainty on the adopted values for each cluster is about ± 0.05 mag.

3. COMPARING THEORY AND OBSERVATIONS

A 25 kpc linear size galaxy at redshift z in a $q_0 = 0$ universe is about $1.8h(1+z)^2/[z(1+z/2)]$ arcsec across (here $H_0 = 100h$ km s^{-1} Mpc^{-1}). Its surface brightness dims as $(1+z)^{-4}$ and the seeing effect tends to erase any morphological feature. As a result, the faintest outermost envelopes of the distant galaxies quickly fade to unfavorable S/Ns and it becomes very difficult or impossible to estimate the morphology at high redshift. Indeed, beyond $z \sim 0.2$ any direct morphological classification might become unreliable even in deep CCD frames when taken under standard instrumental and seeing conditions. That is why we must rely on colors to identify elliptical galaxies in our clusters.

The expected colors in a $(H_0, q_0) = (50, 0)$ universe as a function of redshift for evolving early-type galaxies have been derived in Molinari et al. (1990, their Fig. 18) based on Buzzoni's (1989) population synthesis code. In that work evolutionary effects of a burst stellar population were accounted for in excess to the canonical k-correction induced by the passive redshift of the galactic present-day spectral energy distribution. In the broad-band colors considered, the effect of evolution is a little systematic blueing of younger galaxies with respect to the simple k-correction up to about $\Delta(g-r) \sim 0.12$ and $\Delta(g-i) \sim 0.16$ for galaxies at $z = 0.5$.

As it will be clear in the next section, the test rests on a reliable fit of the observations with the theoretical evolutionary tracks in the phase space of the three parameters H_0, q_0, and z_f (the redshift of galaxy formation). In order to secure on more solid grounds our conclusions it is, however, essential to assess first some preliminary but possibly relevant questions.

3.1. *Metallicity*

It has been well established that integrated colors in stellar populations are a function of both age and metallicity. Both parameters display very similar effects since by either increasing age or metallicity we end up with redder colors (for an exhaustive discussion on this subject in relation to the problem of dating galaxies see, for example, Renzini & Buzzoni 1986 and references therein). It is also a widely accepted conclusion that elliptical galaxies are dominated by metal-rich stellar populations with [Fe/H] possibly higher than the solar value (Burstein 1979; Frogel, Persson, & Cohen 1980; Terlevich et al. 1981; Burstein et al. 1984). In addition, [Fe/H] should be even larger for giant galaxies according to the Visvanathan & Sandage (1977) c-m correlation, indicating that colors are redder in more luminous galaxies.

A wrong or poor assumption about the galactic metallicity might affect our results. Assuming, for instance, [Fe/H] = 0 in the reference evolutionary models we would predict slightly bluer colors at a given age (redshift). As a consequence, comparing with observations one would infer an older age for the universe because older (redder) galaxies would be required to fit the data. It is clear therefore that we need first to know fairly well the galactic [Fe/H] if we want to confidently reproduce the genuine variation in the colors due to the age effects as a function of redshift. Buzzoni, Gariboldi, & Mantegazza (1992) studied the metallicity distribution of nearby early-type galaxies through the Mg_2 index deriving [Fe/H] in the range $+0.06/+0.21$ as mean representative values. This means that elliptical galaxies exceed the solar value typically by about 50%.

3.2. *Reddening*

Galactic absorption is nicely dealt with by using the discrete method developed by Burstein & Heiles (1982). We used their results to correct data for Galactic reddening assuming $E(g-r) = 1.10E(B-V)$ and $E(g-i) = 1.73E(B-V)$.

Internal absorption is not known so well. However, following the observations by Valentijn (1990) we could assume galaxies to be optically thick and make predictions about the radiative transfer across. Calculations by Bruzual, Magris, & Calvet (1988) show that we should expect low values for the color excess $E(B-V)$, and similar conclusions are supported empirically also by Buzzoni et al. (1992) suggesting $E(B-V)_{\rm ell} \leq 0.04$ for elliptical galaxies at the present time.

Of course, the matter could be different at very high redshift where star formation could be still at work. In that case the reddening due to internal absorption could partially compensate for the blueing introduced by the younger stellar populations, masking, therefore, evolution. Any effect in this sense however could hardly be relevant in our range of distance (i.e., $z < 0.5$). Therefore, no correction for internal absorption was applied to our data.

3.3. *Composite Stellar Populations*

Are elliptical galaxies reasonably well described by an old simple stellar population with fixed age and metallicity? Indeed, star formation might have occurred in principle also in a more recent stage of the life of galaxies. In that case colors would be strongly affected by the presence of a younger stellar component. Alternatively, a quick chemical enrichment in the early stages could have led to a spread in metallicity among virtually coeval (old) stellar populations.

Observations of high-redshift ellipticals in clusters and in the field show that their color distribution in the rest frame has a smaller spread from the blue to the infrared (Couch et al. 1983; Dunlop et al. 1989) while it increases in the UV (MacLaren, Ellis, & Couch 1988). In addition, as we mentioned above, the optical colors of galaxies in clusters display a mild and coherent blueing with increasing redshift that can be fully accounted for by evolutionary models with a primeval burst stellar population (Couch et al. 1983; Molinari et al. 1990). Similar conclusions stem also from the work of Hamilton (1985) on the basis of a detailed study of the 4000 Å break in field galaxies at high redshift. He suggested that elliptical galaxies in his observed sample are a basically coeval class of objects with only a ± 2 Gyr age dispersion and are consistent therefore with a single-burst stellar population.

Concerning a possible spread in metallicity among coeval old stellar populations, this can be predicted theoretically by the models of galaxy evolution (cf., for example, Arimoto & Yoshii 1987). It is unlikely however that this spread could introduce any important effect as the extremely metal poor component would give a practically null contribution at the relevant wavelengths of our observations. Moreover, it is clear that a large fraction of the galactic light at present day is provided by the metal-rich stars (Buzzoni et al. 1992).

In conclusion, it seems to be fully reasonable to describe the overall spectral energy distribution of elliptical galaxies longward of 2500 Å in terms of simple stellar populations of a proper "effective" metallicity (see, for example, Fig. 3 in Bruzual 1992 for an eloquent comparison). Nonetheless, the apparent spread in the UV shortward 2500 Å might be a sign for some perturbing mechanism at work possibly dealing with the problem of the blue galaxies excess in the distant clusters first suggested by Butcher & Oemler (1984). In any case, the blue galaxies' excess would introduce a negligible bias due to our adopted selection criteria as discussed in § 2.

4. THE COSMOLOGICAL TEST

4.1. *Dating Elliptical Galaxies*

Our test is based on a proper calibration of the cosmological clock relating absolute time with redshift. By dating galaxies at the present time we would give a direct constraint on the cosmological time and then on the value of the Hubble constant. In addition, by estimating the rate of change in the relative age of galaxies with different redshift we would provide an indirect measure of the deceleration parameter q_0.

The point is summarized in Figure 1 where the relative age of the universe is calculated for two relevant choices of $q_0 = 0$ (a virtually empty universe) and $\frac{1}{2}$ (i.e., an Einstein–de Sitter model discriminating between open and closed models). As it could be relevant for our subsequent discussion to consider age variations with respect to the value at $z = 0.2$ we normalized time at this redshift in the figure. One sees that different predictions for $z = 0$ stem for the two cases. In an Einstein–de Sitter

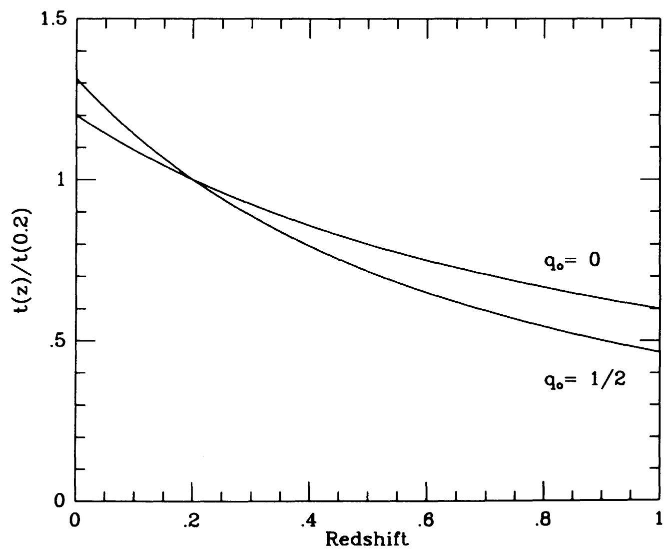

FIG. 1.—The relative age of the universe vs. redshift for two choices of the deceleration parameter, $q_0 = 0$ (virtually empty universe) and $\frac{1}{2}$ (Einstein–de Sitter universe). The age is normalized at $z = 0.2$ to ease the comparison with the observational data base (see text for discussion).

metrics time "runs" slightly faster with redshift, and a 31% excess is expected for the age of present-day galaxies. On the contrary, only a 20% excess in current age is predicted adopting $q_0 = 0$. It is worth stressing that these expectations are valid independently of any direct knowledge of H_0 (that would be necessary however to set up the absolute age).

As shown in Table 1, our observational sample consists basically of two groups of clusters: a major group of six clusters at intermediate redshift, around $z \sim 0.2$, and three more sparse distant clusters between $0.32 < z < 0.50$. A preliminary estimate of the galactic age at different redshifts can be derived from the two panels of Figure 2. Here observations are compared with a theoretical grid of k-corrected models assuming different ages taken from Buzzoni (1989, his set of models with [Fe/H] = +0.23 and Salpeter IMF). We recall that no assumption about cosmological parameters is done by calculating the theoretical color paths in the figure as we are simply redshifting the theoretical models with fixed age.

Consider first the group of clusters at a nominal mean $z = 0.17 \pm 0.04$. It is remarkable to note from Figure 2 that they seem to form a very coherent sample with nearly the same age. Using our adopted code for evolutionary population synthesis and comparing with both observed $g - r$ and $g - i$, one can immediately derive for these clusters an absolute age of 12 Gyr. Moreover, they seem to be coeval within ± 3 Gyr at 1 σ level.

Extending our analysis also to the three more distant clusters (with a mean $z = 0.42 \pm 0.10$), we note that uncertainties in the color transformation prevents any accurate determination of the absolute age of S0400. What definitely stems considering only Cl 2158+0351 and Cl 1141−283a in both the $g - r$ and $g - i$ diagrams of Figure 2 is that their observed colors seem consistent with stellar populations *not dramatically younger* with respect to the low-redshift group. A value of 11 ± 3 Gyr might be a realistic estimate of the galactic age at $z = 0.45$. Accounting for photometric uncertainties we are also inclined to take 8 Gyr as a confident lower limit for the age of the high-redshift clusters in our sample.

One supplementary point could be included in our discussion concerning the assumed age of the elliptical galaxies at present time. Despite the wide spread of opinions about the possibility that star formation could have taken place in these galaxies up to 5 Gyr ago (O'Connell 1980) there is general agreement that the bulk of stellar populations in ellipticals is mainly formed by old stars. In their study about metallicity calibration of elliptical galaxies in the Davies et al. (1987) local sample, Buzzoni et al. (1992) concluded that properties of galaxies at $z = 0$ are consistent with a 15 Gyr stellar population. Ages about 13–14 Gyr stem also from the models of population synthesis by Rocca-Volmerange (1989) and Bruzual (1992).

4.2. *Fitting with Friedmann Models*

The grid of k-corrected models considered in Figure 2 provides the basic theoretical data to compute reference evolutionary sequences for different choices of the cosmological parameters. We adopted first a classical Friedman cosmology with $\Lambda_0 = 0$ in order to explore H_0 and q_0. Calculations of expected color evolution were performed as a function of the redshift of galaxy formation (in the range $3 \leq z_f \leq \infty$), the deceleration parameter ($0 \leq q_0 \leq 1$), and the Hubble constant ($20 \leq H_0 \leq 100$ km s^{-1} Mpc^{-1}). Theoretical colors were derived consistently in the ESO Gunn system taking into account the instrumental response of filters and CCD.

Before attempting any fit to the data a preliminary comparison with two relevant sets of cosmological models can help to clarify the expected amount of evolution at large redshift allowing therefore some qualitative conclusions about our test performances. In Figure 3 we report the two cases with $q_0 = 0$ and $\frac{1}{2}$ assuming both $H_0 = 50$ and 100 km s^{-1} Mpc^{-1}. We stress that the evolutionary sequences in the figure are *not* a fit to the data but only display the theoretical expectations for those specific choices of the relevant cosmological parameters. It is quite evident from the figure that data favor low values both for q_0 and H_0. This directly derives from our previous conclusions about galactic age versus redshift. Basically, the

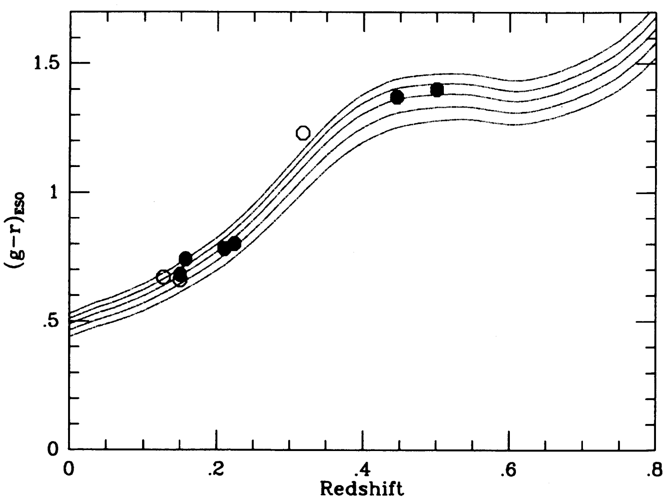

Fig. 2*a*

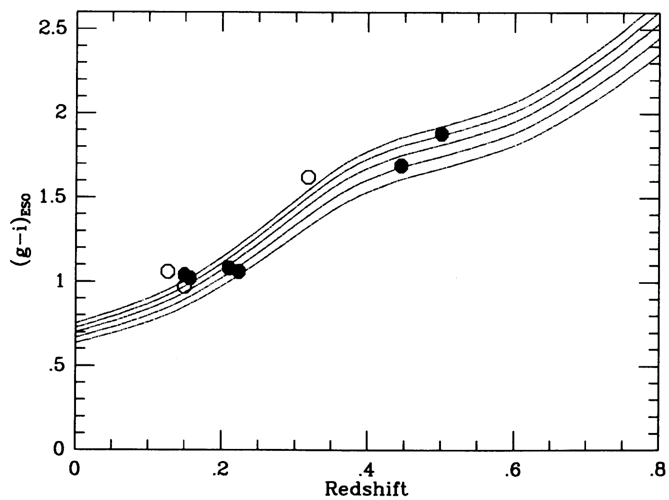

Fig. 2*b*

Fig. 2.—Comparison between observed colors for cluster elliptical galaxies and theoretical models for population synthesis. Displayed are k-corrected models for fixed age 15, 12.5, 10, 8, and 6 Gyr (moving to bluer colors in each sheaf of curves) taken from Buzzoni (1989, his set with [Fe/H] = +0.23 and Salpeter IMF).

In the two panels filled dots represent the mean colors for ellipticals in our sample while open dots mark the three clusters taken from Garilli, Maccagni, & Vettolani (1991) and Garilli et al. (1992). Observations have been corrected for Galactic reddening according to Table 1.

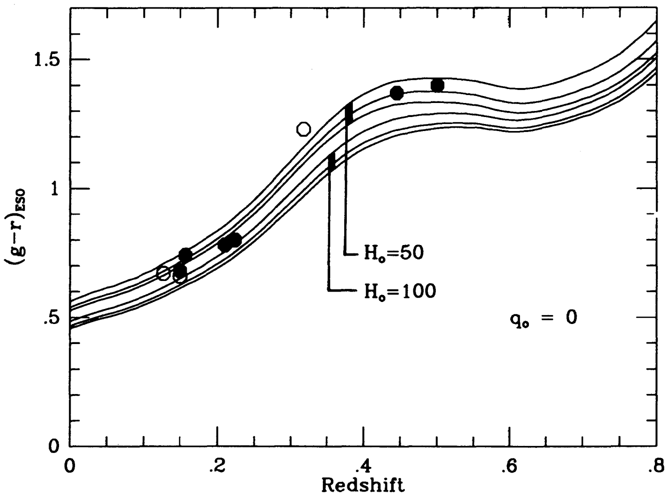

FIG. 3a

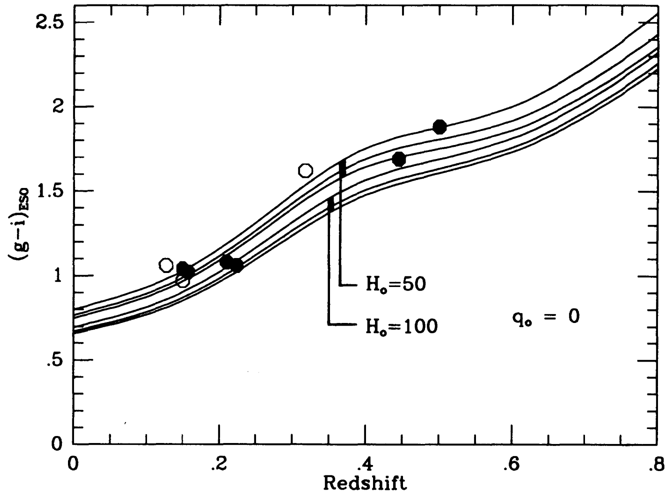

FIG. 3b

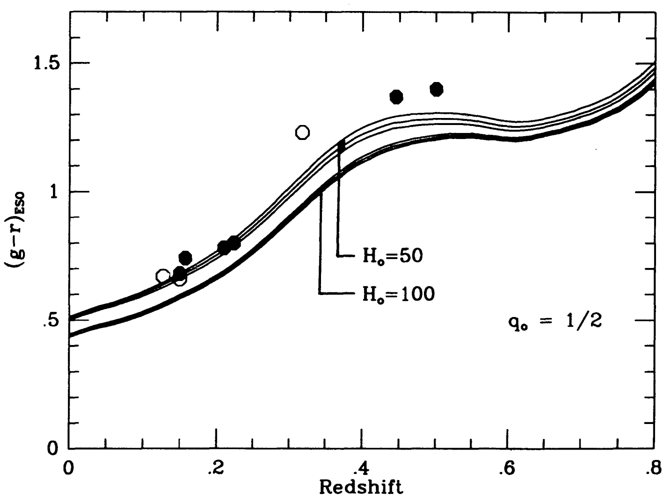

FIG. 3c

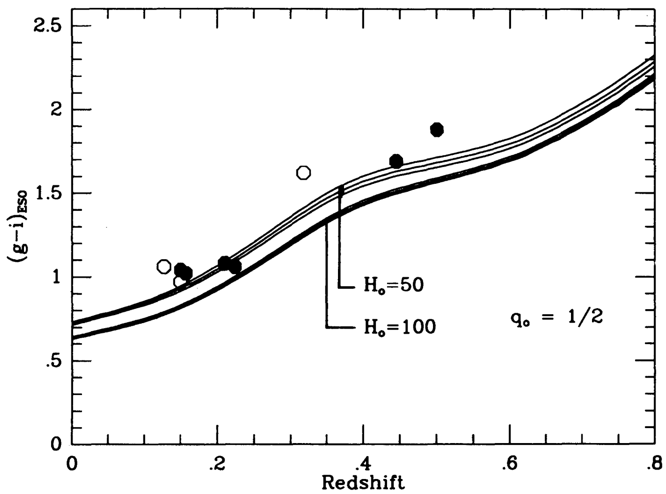

FIG. 3d

FIG. 3.—Comparison between observed colors for cluster ellipticals and evolutionary sequences expected for two relevant sets of cosmological models. Theoretical color evolution is computed starting from models of Fig. 2.

Two families of curves have been computed according to $H_0 = 50$ and 100 km s^{-1} Mpc^{-1}, as labeled in the panels. For each value of H_0 we assumed $z_f = 3$, 5, and ∞ (moving from the bluest to the reddest curve respectively). Data markers are as in Fig. 2.

low value for H_0 is required by the large absolute age of galaxies at $z \sim 0.2$ while a low deceleration parameter is needed in order to match the mild amount of color evolution observed. Large values for q_0 would be even more severely ruled out if we assume galaxies to be formed more recently than the big bang.

A more quantitative analysis of the data can be performed by comparing with a grid of fitting evolutionary sequences for any allowed combination of H_0, q_0, and z_f. Fits were achieved through an iterative algorithm within a typical scatter of ± 0.05 mag in both colors. The permitted range of solutions in the (H_0-q_0) phase space is shown in Figure 4. In the figure we also added a 1 σ error strip calculated for the case of $z_f = \infty$. The expected uncertainty was simply obtained in this case for fixed values of q_0 by fitting each cluster with a suitable value of H_0, and determining then $\sigma(H_0)$ from the whole sample of points.

Expected colors of elliptical galaxies at present time derived from the fitting grid of models are $(g - r)_0 = 0.53 \pm 0.02$ and $(g - i)_0 = 0.75 \pm 0.03$ (colors are intended in the ESO system). This is consistent with an age of 16 ± 2 Gyr at $z = 0$ in good agreement with the current estimates. We note by the way that uncertainty in this estimate might be larger than its formal statistical error as it is implicitly based on the canonical scenario for stellar evolution assumed in the synthesis computational code. As we showed in previous subsection, a fit with simply k-corrected models (i.e., without accounting for evolution) would lead to an age up to 20% younger.

Just a glance at Figure 4 allows us to estimate a firm upper limit for H_0 at 68 km s^{-1} Mpc^{-1}. This seems to fully support the most recent determination of $H_0 = 52 \pm 2$ obtained by Sandage & Tammann (1990) using observations of the Virgo Cluster. In addition, authors conclude that a lower limit for the Hubble constant could be placed at 45 ± 3 km s^{-1} Mpc^{-1}, a value that would also fit with our data. From Figure 4, however, it is also evident that a closed universe could be hardly supported even for this extreme choice of H_0 and only exceedingly low values about 36 ± 5 km s^{-1} Mpc^{-1} would be required. This marginally meets the range derived using super-

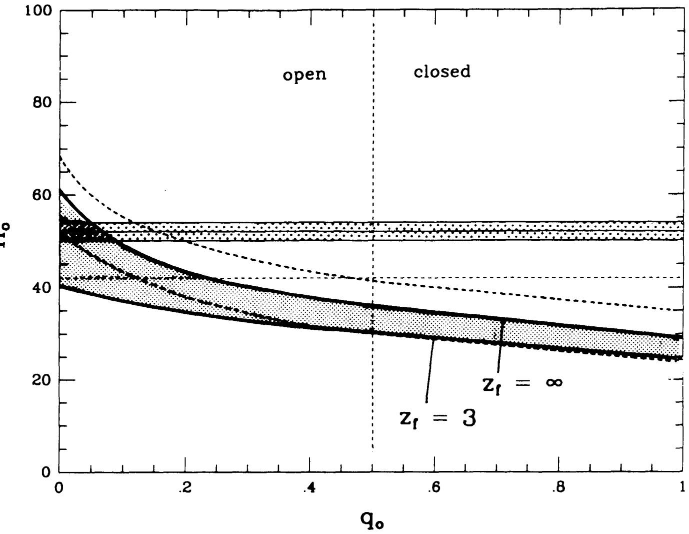

FIG. 4.—Allowed combinations between H_0 and q_0 in a classical Friedmann cosmology as it derives from the fit to the data. The shaded strip is the solution with the redshift for galaxy formation z_f ranging from 3 (*lower edge*) to ∞ (*upper edge*). An upper 1 σ envelope is also traced (*dashed line*). The horizontal strip at $H_0 = 52 \pm 2$ is the value suggested by Sandage & Tammann (1990) with a lower limit at 42 km s^{-1} Mpc^{-1}, also reported in the figure. Vertical line separates open and closed models of universe.

novae as standard candles (Branch et al. 1983; Cadonau, Sandage, & Tammann 1985). With $H_0 = 52 \pm 2$, and assuming galaxies to form at the big bang (i.e., $z_f = \infty$) the formal solution of the fit to data indicates $q_0 = 0.06^{+0.14}_{-0.06}$. With $H_0 = 45 \pm 3$ a conservative upper limit is placed at $q_0 \leq 0.46$.

A confident estimate of the redshift of galaxy formation is still a debated question. Indeed, discordant conclusions in this regard have been reached by different authors. Wyse (1985) suggested that galaxies could have formed very recently at $z_f < 3$, while a comprehensive analysis by Yoshii & Takahara (1988), and Eisenhard & Lebofsky (1987) led to $3 < z_f < 5$ (all these authors use $H_0 = 50$ km s^{-1} Mpc^{-1}). Considering a sample of radio galaxies Dunlop et al. (1989) conclude that the redshift for galaxy formation might be larger than 10. Using the value of H_0 of Sandage & Tammann (1990), and accounting for the quoted uncertainties in our analysis, from Figure 4 we derive that galaxies could have formed more likely beyond $z_f = 5$. A more recent epoch of formation would not be so strongly favored as it would induce much more evolution than observed requiring therefore larger cosmological time scales (i.e., lower values for H_0) in order to properly "dilute" the color change of galaxies and match the observations.

4.3. *Models with $\Lambda_0 \neq 0$: Inflationary Scenarios*

Various inflation theories support cosmological models with $\Omega_0 = 1$. As is well known, this seems to be clearly in conflict with the observational evidences. Indeed, both tests involving photometry and/or counts of distant galaxies derive a lower range for the density parameter strongly supporting an open model for the universe (Eisenhard & Lebofsky 1987; Yoshii & Takahara 1988; Fukugita et al. 1990; Guiderdoni & Rocco-Volmerange 1990).

Two ways out could be invoked to meet the inflationary scenario. The number density invariance could be relaxed in the galaxy counts, for example, by merging-driven evolution at high redshift (Rocca-Volmerange & Guiderdoni 1990). In alternative, we could consider a slightly more complex metrics with a nonzero cosmological constant (Peebles 1976; Tayler 1986; Fukugita et al. 1990). The second possibility seems to be the more attractive one as it still keeps control of what we might know at present.

Expressing the cosmological constant in normalized units such as $\lambda_0 = 1/3\Lambda_0(c/H_0)^2$, the zero-curvature condition becomes $\Omega_0 + \lambda_0 = 1$, and Ω_0 is related to q_0 by the following relation: $q_0 = 3/2\Omega_0 - 1$. The range of fitting solutions in this case are summarized in Figure 5, where for the sake of clarity we also plotted in the lower panel the combined relations among q_0, Ω_0, and λ_0. Three main conclusions can be drawn.

i. The value required for λ_0 is fairly large. It cannot be lower than 0.35, and using $H_0 = 52 \pm 2$ we derive $0.6 \leq \lambda_0 \leq 0.85$. As a consequence, $\Omega_0 < 0.65$ with the optimum range given by $0.15 \leq \Omega_0 \leq 0.4$. These conclusions fully agree with those reached by Fukugita et al. (1990) on the basis of an independent test using deep galaxy counts.

ii. The deceleration parameter is negative and assumes values in the range $-0.8 \leq q_0 \leq -0.4$. The positive acceleration implies that the Hubble time scale $1/H_0$ is only a lower limit for the age of the universe so that larger values are permitted in spite of the old galactic age.

iii. H_0 is not so strongly constrained as in the models with zero-cosmological constant. While we still need to have rather small values for it if $\Omega_0 \to 1$, at lower values for the density parameter about 0.1 (as the observations of bright matter seem to indicate) H_0 must exceed 50 turning to be in the range about 60–80 km s^{-1} Mpc^{-1}. Remarkably, this would fit both with a preferred low-density scenario and with the estimate of the Hubble constant as derives from the Tully-Fisher relation (Han & Mould 1990).

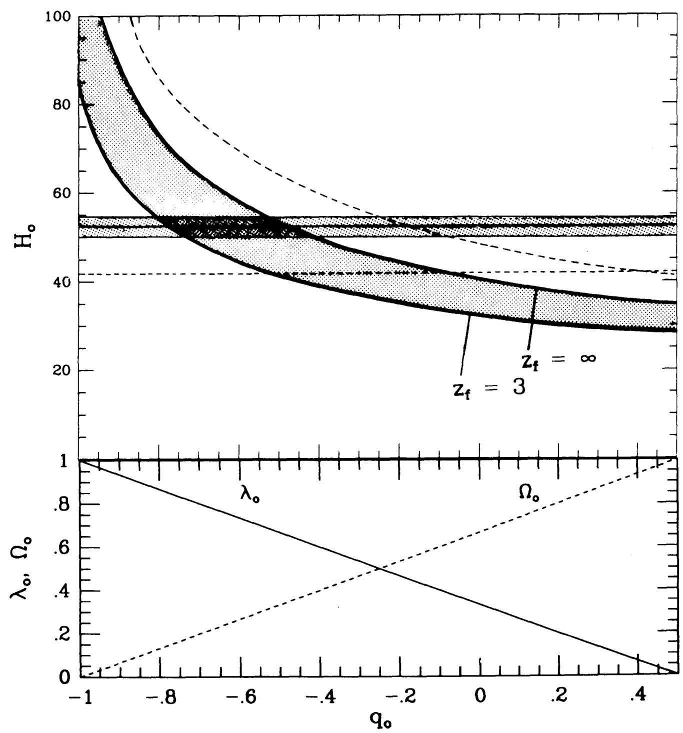

FIG. 5.—Same as Fig. 4 but for the case of a zero-curvature space with $\Lambda_0 \neq 0$. See text for discussion about the combined relationship of the different relevant cosmological parameters.

5. CONCLUSIONS

In this work we have compared observed colors of elliptical galaxies in distant clusters with reference evolutionary models derived from Buzzoni's (1989) population synthesis code deriving useful constraints to the values of the cosmological parameters.

Galaxies at $z = 0.2$ seem coeval within ± 3 Gyr indicating an absolute age of 12 Gyr. The look-back time from $z = 0.2$ to $z = 0.45$ is found to be not larger than 4 Gyr. In a classical Friedmann cosmology, assuming a zero cosmological constant, this leads to estimate a current age of the universe of 16 ± 2 Gyr, while H_0 must be less than 68 km s^{-1} Mpc^{-1}. Assuming $H_0 = 52 \pm 2$ from Sandage & Tammann (1990) we derive $q_0 = 0.06^{+0.14}_{-0.06}$. Galaxies should form in this framework at redshift larger than 5.

An Einstein–de Sitter universe is ruled out unless we assume exceedingly low values for the Hubble constant ($H_0 \leq 41$ km s^{-1} Mpc^{-1}) or account for models with nonzero cosmological constant. In this case we find that the normalized cosmological constant λ_0 must be larger than 0.35 with a best value in the range $0.6 \leq \lambda_0 \leq 0.85$ (accordingly, $0.15 \leq \Omega_0 \leq 0.4$ with a conservative upper limit of 0.65).

In the case of a $\Lambda_0 \neq 0$ model a larger value for the Hubble constant ($H_0 = 60$–80 km s^{-1} Mpc^{-1}) and a low-density parameter ($\Omega_0 \sim 0.1$) could be reconciled.

We wish to thank the ESO staff at La Silla for the competent support during the various observing runs. The anonymous referee is also acknowledged for his/her useful comments and suggestions that timely focused some relevant points in the discussion of the results and greatly contributed to the improvement of the original version of the paper.

REFERENCES

Abell, G. O., Corwin, H. G., Jr., & Olowin, R. P. 1989, ApJS, 70, 1
Arimoto, N., & Yoshii, Y. 1987, A&A, 173, 23
Binggeli, B., Sandage, A., & Tammann, G. A. 1988, ARA&A, 26, 509
Branch, D., Lacy, C. H., McCall, M. L., Sutherland, P. G., & Uomoto, A. 1983, ApJ, 270, 123
Bruzual, G. 1992, in The Stellar Population of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 311
Bruzual, G., Magris, G., & Calvet, N. 1988, ApJ, 333, 673
Burstein, D. 1979, ApJ, 232, 74
Burstein, D., Faber, S. M., Gaskell, C. M., & Krumm, N. 1984, ApJ, 287, 586
Burstein, D., & Heiles, C. 1982, AJ, 87, 1165
Butcher, H., & Oemler, A., Jr. 1984, ApJ, 285, 426
Buzzoni, A. 1989, ApJS, 71, 817
Buzzoni, A., Gariboldi, G., & Mantegazza, L. 1992, AJ, 103, 1814
Buzzoni, A., Molinari, E., Manousoyannaki, I., & Chincarini, G. 1988, Messenger, 53, 50
Cadonau, R., Sandage, A., & Tammann, G. A. 1985, in Supernovae as Distance Indicators, (Lect. Notes Phys.), ed. N. Bartel (Berlin: Springer), 15
Couch, W. J., Ellis, R. S., Godwin, J., & Carter, D. 1983, MNRAS, 205, 1287
Davies, R. L., Burstein, D., Dressler, A., Faber, S. M., Lynden-Bell, D., Terlevich, R. S., & Wegner, G. 1987, ApJS, 64, 581
Dressler, A., & Gunn, J. E. 1992, ApJS, 78, 1
Dunlop, J. S., Guiderdoni, B., Rocca-Volmerange, B., Peacock, J. A., & Longair, M. S. 1989, MNRAS, 240, 257
Eisenhard, P. R., & Lebofsky, M. J. 1987, ApJ, 316, 70
Frogel, J. A., Persson, S. E., & Cohen, J. G. 1978, ApJ, 240, 785
Fukugita, M., Takahara, F., Yamashita, K., & Yoshii, Y. 1990, ApJ, 361, L4
Garilli, B., Bottini, D., Maccagni, D., Vettolani, G., & Maccacaro, T. 1992, submitted to AJ
Garilli, B., Maccagni, D., & Vettolani, G. 1991, AJ, 101, 795
Guiderdoni, B., & Rocca-Volmerange, B. 1990, A&A, 227, 362
Gunn, J. E., Hoessel, J. G., & Oke, J. B. 1986, ApJ, 306, 30
Hamilton, D. 1985, ApJ, 297, 371
Han, M., & Mould, J. 1990, ApJ, 360, 448
Kristian, J., Sandage, A., & Westphal, J. A. 1978, ApJ, 221, 383
Lebofsky, M. J. 1978, ApJ, 245, L59
Lilly, S. J., & Longair, M. S. 1984, MNRAS, 211, 833
Loh, E. D., & Spillar, E. J. 1986, ApJ, 307, L1
Luppino, G. A., Cooke, B. A., Hardy, I. M., & Ricker, G. R. 1991, AJ, 102, 1
McLaren, I., Ellis, R. S., & Couch, W. J. 1988, MNRAS, 230, 249
Melnick, J., Dekker, H., & D'Odorico, S. 1989, ESO Operating Manual, No. 4 (Garching: ESO)
Molinari, E., Buzzoni, A., & Chincarini, G. 1990, MNRAS, 246, 576
Molinari, E., Buzzoni, A., Longhetti, M., & Chincarini, G. 1992a, in Observational Cosmology, ed. G. Chincarini et al. (ASP Conf. Ser.), in preparation
Molinari, E., Pedrana, D., Banzi, M., Buzzoni, A., & Chincarini, G. 1992b, in IAU Symp. 149, Stellar Populations of the Galaxies, ed. B. Barbuy (Dordrecht: Kluwer), 460
Molinari, E., Pedrana, D., Banzi, M., Buzzoni, A., & Chincarini, G. 1992c, A&AS, submitted
O'Connell, R. W. 1980, ApJ, 236, 430
Pedersen, H. 1988, private communication quoted by Garilli, Maccagni, & Vettolani (1991)
Peebles, P. J. E. 1976, ApJ, 205, 318
Pickles, A. J., & van der Kruit, P. C. 1991, A&AS, 91, 1
Renzini, A., & Buzzoni, A. 1986, in Spectral Evolution of Galaxies, ed. C. Chiosi & A. Renzini (Dordrecht: Reidel), 195
Rocca-Volmerange, B. 1989, MNRAS, 236, 47
Rocca-Volmerange, B., & Guiderdoni, B. 1990, MNRAS, 247, 166
Sandage, A. 1988, ARA&A, 26, 561
Sandage, A., & Tammann, G. A. 1990, ApJ, 365, 1
Schneider, D. P., Gunn, J. E., & Hoessel, J. G. 1983, ApJ, 264, 337
Searle, L., Sargent, W. L. W., & Bagnuolo, W. 1973, ApJ, 179, 247
Sinclaire, P. 1987, CCD Detectors Available at La Silla (La Silla: ESO)
Tayler, R. J. 1986, QJRAS, 27, 367
Terlevich, R., Davies, R. L., Faber, S. M., & Burstein, D. 1981, MNRAS, 196, 381
Tinsley, B. M. 1972, A&A, 20, 383
Thuan, T. X., & Gunn, J. E. 1976, PASP, 88, 543
Valentijn, E. A. 1990, Nature, 346, 153
Visvanathan, N., & Sandage, A. 1977, ApJ, 216, 214
West, R. M., & Frandsen, S. 1981, A&AS, 44, 329
West, R. M., & Kruszewski, A. 1981, Irish Astron. J., 15, 25
Wyse, R. F. G. 1985, ApJ, 299, 593
Yoshii, Y., & Takahara, F. 1988, ApJ, 326, 1