SPECTRAL EVOLUTION OF GALAXIES: CURRENT VIEWS(*)

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RESUMEN. En este trabajo se presenta un resumen de los puntos de vista actuales en cuanto a la interpretación de las observaciones destinadas a detectar evolución espectral en galaxias. Se concluye que la evolución detectada en las muestras conocidas de galaxias es un proceso lento (quizás consistente con la ausencia de evolución) y que las fases tempranas de rápida evolución espectral no han sido detectadas todavía.

ABSTRACT. This paper presents a summary of current views on the interpretation of the various evolutionary tests aimed at detecting spectral evolution in galaxies. It is concluded that the evolution taking place in known galaxy samples is a slow process (perhaps consistent with no evolution at all), and that the early phases of rapid spectral evolution in early-type galaxies have not been detected yet.

I. INTRODUCTION

Even though at first sight galaxies seem to be very old and unchanging systems, there are several lines of observational evidence and theoretical arguments that point towards the fact that many galaxian properties are functions of time. Some of these properties, such as the stellar population and gas content, the chemical composition of stars and gas, the integrated rest frame spectral energy distribution, (s.e.d.), color, and luminosity are readily recognizable as properties that should show a time dependence. The quantitative determination of the time variation of these properties is far from complete. The slow rate of change of these properties requires observations of galaxies seen at cosmological epochs separated by a sizeable fraction of the age of the universe and of the age of the galaxies themselves. These observation are thus at the limit of present day astronomical instrumentation and definite progress in this area will most likely come with the new generation of telescopes and electronic light detectors. Existing data allow only very crude comparisons with predictions of the theoretical models required to interpret these data.

At a more fundamental level there are quantities such as the star formation rate (SRF) and the initial mass function (IMF) that determine the time behavior of the properties mentioned above. These functions cannot be measured directly over cosmological time scales, and at most a range of allowed functional forms can be inferred from the range of observed values of directly observable properties. Thus in a way our knowledge about the IMF and the SFR is more uncertain than the conclusions derived from the empirical interpretation of the data alone.

Despite these difficulties considerable time and effort has been invested during the last few years compiling a large body of data on faint galaxy multi-band photographic and photoelectric photometry and spectrophotometry (Windhorst, Kron, and Koo 1983, Thuan *et al.* 1984, Ellis 1983, Lilly 1983, Spinrad, private communications). The quality of the data is high enough that some conclusions and general trends can already be established. These trends should serve to throw light in our understanding of galaxy evolution and help planning future observations both with existing telescopes and telescopes to come.

In this paper I present a summary of our current understanding of the subject of spectral evolution of galaxies. The amount and quality of the data do not allow to disentangle the different effects of stellar and chemical evolution in galaxy spectra. The conclusions derived in this paper will then rest on the assumption that the changes claimed to be observed in galaxy spectra are only due to the normal evolution of a stellar population of constant metallicity. The empirical data and theoretical models needed to interpret spectral evolution are described in II. The results from various tests are shown in III. The conclusions are presented in IV.

II. TESTING SPECTRAL EVOLUTION

Any observational test that is used to probe spectral evolution of galaxies rests on a comparison of the spectra of nearby and distant galaxies. These tests can be performed directly by comparing the s.e.d.'s of different galaxies, or indirectly by using indicators of the shape of the s.e.d.'s (e.g., broad-band colors or magnitudes, galaxy number counts and color distributions). In both cases the observed s.e.d.'s of nearby galaxies are used to predict the values that the galaxy properties should have in the absence of spectral evolution. Any difference between the observed and predicted values can be taken as empirical evidence of spectral evolution in galaxies, provided that one can insure that the galaxies under consideration are identical in all respects except in their ages. Moreover, since the observations are perfomed over a region of finite physical size in the galaxy rest frame, all efforts should be made to sample equal regions in nearby and distant galaxies. This is particularly important since radial color and metallicity gradients known to exist in galaxies can mimic the effects of spectral evolution when the more distant systems are sampled over a larger physical region than the nearby ones by means of a fixed-size aperture (Oke, Bertola, and Capaccioli 1981, Bruzual 1983a).

In order to interpret the detected changes in galaxy spectra detailed models that incorporate the effects in galaxy s.e.d.'s of an aging stellar population are required. A set of such models is described below.

(a) Nearby Galaxy S.E.D.'s.

From the previous discussion it is clear that the detection of spectral evolution in galaxies rests heavily on our knowledge of the s.e.d. of nearby galaxies. The UV region of the spectrum is of particular importance, since for cosmologically interesting redshifts this is the spectral region most often observed from the ground.

Figure 1 shows in a log-log scale an s.e.d. which is representative of the s.e.d. of elliptical galaxies in the range from 1500 to 3400 Å. In the UV region the s.e.d. was obtained from the average of the *IUE* spectra of M31 (central bulge), M32, and NGC 4472 (Bruzual 1983b). No smoothing has been applied to these data. Even though some elliptical galaxies, like NGC 4486 (Bertola *et al.* 1980, Perola and Tarenghi 1980) and NGC 4649 (Bertola, Capaccioli and Oke 1982), have UV spectra markedly steeper shortward of 2000 Å than the average shown here, this average s.e.d. seems to apply to a vast majority of elliptical galaxies (Ellis 1983). In the optical region the s.e.d. comes from Pence (1976). In the IR monochromatic fluxes were assigned at the effective wavelengths of the J, H, K, and L bands according to published average colors for elliptical galaxies and the standard calibration of the IR color system.

The UV spectrum of spiral and irregular galaxies is in a way more complicated than the UV spectrum of elliptical galaxies. The UV s.e.d.'s show large differences from galaxy to galaxy and from region to region in a given galaxy. The inclusion in the aperture of an active region of star formation shows up as a very steep gradient in the UV shortward of 2000 Å (due to emission from massive stars). Statistical fluctuations in the number of stars included in the detector can produce noticeable differences in the shape of the s.e.d. The average surface brightness over the entire galaxy is lower in spiral and irregular galaxies than in elliptical ones. Thus bright spots are preferentially selected for observation. The effect of dust in the light coming out of these regions is very uncertain and in general is not taken into account when interpreting the existing data. The observed fluxes may then not be completely representative of the integrated emission over the entire region. Because of a combination of all of these factors the average spectrum of late type galaxies of a given morphology is not as well defined as for elliptical galaxies. However, some attempts have been made to group these systems in different color classes (Ellis 1983).

For illustration purposes Fig. 2 shows the spectrum of the irregular galaxy NGC 4449 from the UV to the IR in a log-log scale normalized to $F_\lambda = 1$ at $\lambda = 5500$ Å. This is one of the brightest galaxies in the UV for which detailed spectral information is available. The spectrum shown is the average of the spectra of different regions in this galaxy and was kindly provided by R.S. Ellis. The fluxes reported by Huchra and Geller (1982) for NGC 4214 and NGC 4670 are shown in the same scale.

The interpretation of these spectra in terms of the underlying stellar population is presented in III.

(b) Evolutionary Synthesis Models.

In this section I summarize some of the most relevant aspects from Bruzual (1981, 1983a) evolutionary synthesis models for the spectral evolution of galaxies. For reasons of space only a short summary of the assumptions underlying these models and the notation in use is presented here. The reader is referred to Bruzual (1983a) for more details.

Some of the simplifying assumptions underlying these models are the following: (1) Galaxies can be treated as closed systems. (2) Chemical evolution is not important (for our purposes) after most of the stars in galaxies are formed. The models assume solar chemical composition throughout. (3) The SFR is a smooth function of time (independent of stellar mass) which determines the spectral and luminosity evolution of a galaxy. (4) The IMF is a simple function of the stellar mass (independent of galaxy age) of the same general form as the IMF observed in the solar vicinity. (5) The effects of dust and gas in galaxy spectra can be neglected in a first approximation. The validity of these assumptions lies in the ability of the models to reproduce the observations.

The different types of models, depending on the SFR used, are denoted c- (constant SFR) and μ- (exponential SFR). In the c-models the SFR is constant during a time interval denoted τ, and equal zero for t > τ. In the μ-models the parameter μ, related to the e-folding time τ by

$$\mu \equiv 1 - \exp(-1\ \mathrm{Gyr}/\tau),$$

is used. The quantity μ represents the fraction of galaxy mass that is transformed into stars during the first Gyr of the lifetime of a galaxy. The exponent in the IMF is indicated by (1+x). Details about the stellar evolutionary tracks and s.e.d.'s used in these models can be found in the references already mentioned.

Frequent use is made of cosmological expressions. Friedmann cosmological models with zero cosmological constant have been used. In the reminder of this paper, time will be measured in Gyr (= 1.0E9 yr), and H_o in Km/s/Mpc. In both cases the units will not be indicated. For time, the following notation is used. The age of the universe will be denoted by t_o, the age of galaxies by t_g, and the current value of time by t; τ will always refer to the characteristic time scale appearing in the SFR.

Details about the photometric systems used are given in Bruzual (1983a).

III. RESULTS

(a) Nearby Galaxies

The evolutionary models discussed in the previous section can be used to derive information about the stellar population present in a given galaxy, whose s.e.d. and approximate age are known. A detailed analysis of the subject can be found in Bruzual (1983c). Only the most important results will be mentioned here.

Elliptical Galaxies. It has been known for several years now that the UV flux observed in elliptical galaxies is in excess of the flux expected from the old Population I that dominates the spectrum in the visible region. The problem has been amply discussed in the literature (Wu *et al.* 1980, Bruzual 1983a, c) and several possible sources of the UV radiation have been proposed. Some of the possible sources are:

(1) A population of recently formed main sequence stars with masses well above the 10-12 Gyr turn-off. If that is the case elliptical galaxies are required to have been forming stars in the recent past, or to be forming stars even at the present epoch. A μ = 0.80 model at t_g = 12 with x = 1.35 produces enough UV flux to match the s.e.d. shown in Fig. 1. This synthe-

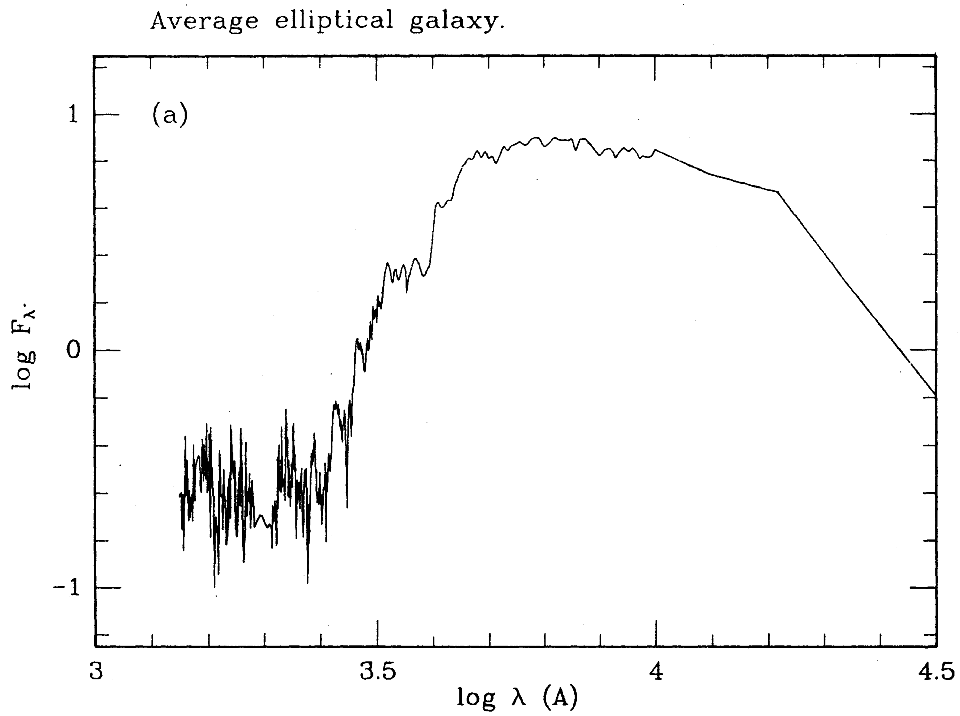

Fig. 1. Average s.e.d. for an elliptical galaxy. The different spectra used to define this average are indicated in the text.

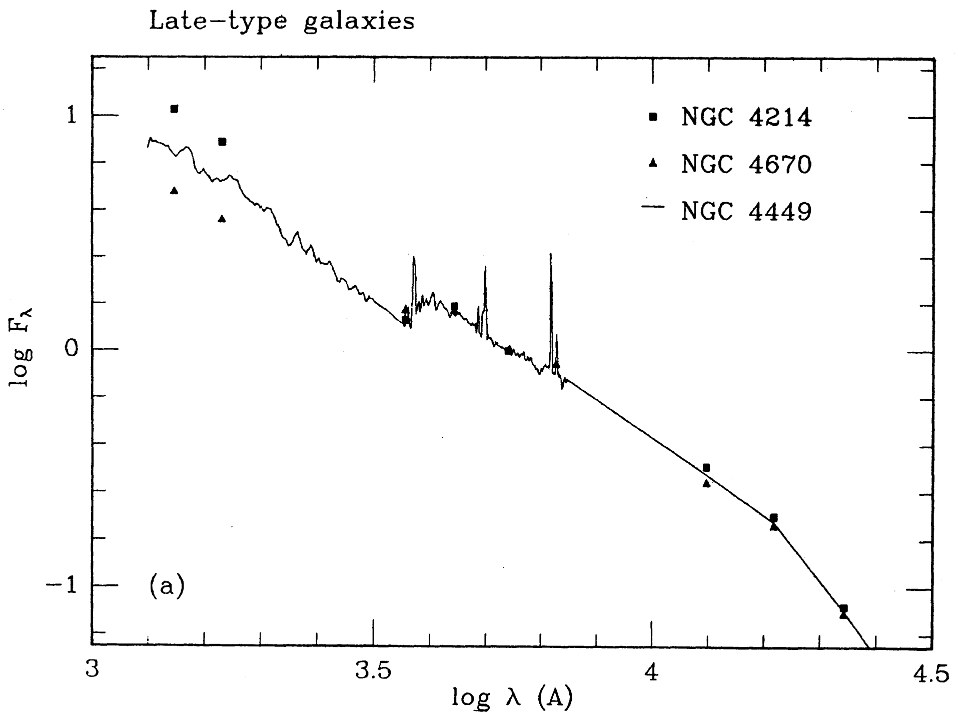

Fig. 2. S.e.d. of NGC 4449 and broad band fluxes of NGC 4214 and NGC 4670. The data have been normalized at 5500 Å.

tic spectrum is shown in Fig. 3. The remaining differences between the observed and synthetic spectra shortward of 2000 Å are of the same order of magnitude as the uncertainties in the matching of the *IUE* SWP and LWR images for faint sources. No attempt to improve the fit to the observed s.e.d. is then justified.

(2) Star formation does not have to be going on continuously throughout the life of the galaxy (as was assumed to build the $\mu = 0.80$ model) in order to obtain enough UV flux. It is possible that bursts of star formation take place randomly distributed in time. As long as we observe the galaxy at the appropriate time after the burst, the UV flux can be reproduced. However, the similarity observed among most elliptical galaxy UV spectra seems to argue against this mechanism. The typical age of the burst responsible of the UV flux has to be $\lesssim$ 1 Gyr. Bruzual (1983c, cf. Fig. 2d) has presented results for such a burst occuring on and old population. The choice of parameters was such that the second burst occuring in a c-model has the same strength (in total mass of gas formed into stars) as the first burst that formed the older population. In this sense this second burst represents a large scale phenomenon. To invoke smaller scale bursts one is required to observe the galaxy much closer to the occurrence of the second burst. These bursts cannot be identified with the one that gave origin to the complete stellar population because the optical part of the spectrum is not reproduced at such short ages.

(3) According to Wu *et al.* (1980) horizontal branch (HB) stars are one of the most likely sources of the UV light in elliptical galaxies. These stars may come either from an underlying metal poor population (which is not prominent in the optical spectrum) or from the metal rich population which produces most of the galaxy light. In the second case large mass loss rates are needed during the giant branch evolutionary phase in order to obtain blue HB stars. Renzini (1981, 1983) estimates that in an old population the HB stars contribute 8 % to the total light, whereas the post-asymptotic and the hot-post-asymptotic giant branch stars together contribute at most 4 % of this flux.

Detailed models for the evolution of a galaxy spectrum that incorporate the HB evolutionary phase are not available. The HB theoretical evolutionary tracks are very sensitive to chemical composition, mass loss rate during the giant branch evolution, and initial stellar mass during the HB evolution. Since these quantities are very poorly known only an *ad hoc* treatment of the HB evolution can be included in the models (see Nesci 1983 and Caloi *et al.* 1984 for an application to globular clusters).

By subtracting the model s.e.d. for an old metal rich population (c-model, $\tau = 1$, $t_g > 12$) from the observed s.e.d. after suitable normalization, the UV flux missing in the model s.e.d. can be expressed as a fraction of the total (bolometric) flux in the observed population. Bruzual (1983c) estimates this fraction to be at most 4-8 % for galaxy ages between 10 and 16 Gyr. This fraction is a slight function of the model age and the normalization chosen. Of course, this number will be higher for *hotter* elliptical galaxies such as NGC 4486 and NGC 4649.

Within the uncertainties of Renzini's theoretical estimate and the observational data, and provided that the HB stars have the appropriate distribution in effective temperature, it seems that the HB stars are better candidates for the source of the UV light than the post-asymptotic giant branch stars. If upper main sequence stars are not the source of the UV light, in principle, Renzini's old population should account for the observed flux at all wavelengths.

(4) There are a few other possible sources of the UV flux: blue stragglers, white dwarfs, interacting binaries, nuclei of planetary nebulae. In general it is estimated that the contribution from these objects is below the detected flux level (Wu *et al.* 1980, Renzini 1981, 1983).

Several arguments have been brought against the idea of recent star formation in elliptical galaxies. Some of these arguments are: (a) In the galaxies observed by *IUE* the UV emitting region seems to be equally extended and uniform as the optical region. Any mechanism of star formation that may be acting in these galaxies must be different to the one producing stars in spiral galaxies. Gas and dust complexes as active regions of star formation are not prominent in elliptical systems. (b) The similarity observed in the UV spectra of most elliptical galaxies (Ellis 1983) seems to favor a stellar source corresponding to a well defined and regularly populated evolutionary stage, instead of random bursts of star formation (or accidental evolutionary stages) which most likely would produce large differences from galaxy to galaxy, as well as among different regions in a given galaxy. (c) The absence of supernovae type II in elliptical galaxies (which should be observed if massive main sequence stars are the source of the UV light) can be explained by assuming a lower upper mass cutoff in the IMF than for spiral galaxies.

The only argument I know of against a Population II HB is the following. The effective temperature of the HB stars increases with decreasing stellar mass and is a sensitive func tion of chemical composition. The expected contribution of this population to the UV galaxy spectrum increases as the galaxy ages. In the absence of any other evolving source, nearby galaxies should be brighter in the UV than distant ones. This does not seem to be the case (at least this is not the dominant effect). Given the uncertainties in the theory of HB evolution this argument should be taken with a word of caution.

In order to establish once and for all the source of the UV in elliptical galaxies what is needed are careful studies in both stars and galaxies of line profiles which are stella luminosity and temperature indicators. Such studies should be able to constrain, for example, the numbers of HB and upper main sequence stars present in a given galaxy.

Late-Type Galaxies: Since late-type galaxies are recognized as regions of active star formation it is reasonable to assume that young, massive main sequence stars are the source of most of the UV emission and of a large fraction of the flux at longer wavelengths. Th theoretical interpretation of the spectrum of late-type systems is uncertain essentially becaus of lack of information about three important quantitites: (a) the slope of the IMF, (b) the age of the dominant population, and (c) the amount of light absorbed by dust (as a function of wave length). Other factors, such as the star formation rate (as long as it is large enough as for young stars to dominate the spectrum), the upper mass limit for star formation, and the chemica abundance, do not seem to be as critical as the ones mentioned above.

In Fig. 4 the spectrum for a $\mu = 0.01$ model at ages = 0.3, 2, and 16 Gyr (top to bottom in the UV range; bottom to top in the IR) is compared with the same data shown in Fig. 2 The following IMF was used to construct the synthetic spectrum:

$$x = 1.0 \quad \text{for} \quad 0.08 < m < 5.00\ m_{\odot},$$

$$x = 2.5 \quad \text{for} \quad 5.0 < m < 25.0\ m_{\odot}$$

This IMF was chosen by the author by trial and error to match the s.e.d. of NGC 444 at 0.3 Gyr and is not based on an *observed* IMF. It is shown here to illustrate the effect of ag on the shape of the s.e.d. Bruzual (1983c) shows similar comparisons for the Salpeter (1955) and the Miller and Scalo (1979) IMF's. The main conclusions derived from this analysis are: (1) for a given age the UV spectrum is very sensitive to the IMF; (2) for a given IMF the UV spectrum is very sensitive to galaxy age; (3) for all the IMF's named above, ages < 1 Gyr seem most likely for the dominant population in these galaxies. If the effect of dust is accounted for, the observed UV fluxes will increase, strengthening this conclusion even more; and (4) the observed spectra are reproduced better by an IMF with a mass dependent x (in the sense of a large value of x for high mass stars than for low mass stars) than by single power laws over the full mass range.

Empirical evidence of variations of the slope of the IMF with the metallicity of th gas in extragalactic systems where violent star formation is taking place has been presented by Terlevich and Melnick (1984). The observed trend implies that the slope of the IMF is a strong function of metallicity given approximately by $x = 4 + \log Z$, over the full mass range. It is not known if this is a universal law that applies to all stellar systems or only to the extragalactic HII regions studied by Terlevich and Melnick. If this behavior is universal, we can understand the higher slope needed for the massive stars in order to reproduce the spectrum shown in Fig. 2 in terms of recent bursts of star formation occurring in metal enriched regions In Terlevich and Melnick analysis it is not established if the upper and lower limit of star formation are also a function of metallicity.

In order to explain the UV spectrum of late-type galaxies of earlier type than NGC 4449 the required ages are not so young as for the latter. Typically values of μ in the range from 0.01 to 0.3 and galaxy ages older than 10 Gyr are required to reproduce these s.e.d.'s (Bruzual 1981, Ellis 1983, Thuan *et al.* 1984).

(b) Evolution of the S.E.D.'s

The determination of changes in the shape of the s.e.d. with galaxy age is not an easy task. In order to measure a noticeable effect, galaxies with redshifts in excess of 0.5 must be observed. Typically these are 23rd blue magnitude galaxies, which means that the signal to-noise ratio in the spectra is very low. The effect is worst in the UV due to the decrease of the emitted flux below 4000 Å. Unfortunately, in the UV is where most of the evolution is expected.

Bruzual (1983c) (cf. his Fig. 2) shows a comparison of four different early-type galaxy spectra with redshifts 0, 0.2, 0.5, and 1.1 in the galaxy rest frame. These comparison shows a slight indication that the more distant galaxies have a higher UV flux than the nearby ones. However, due to the noisy nature of the data it is not possible to derive an accurate quantitative estimate of the rate of spectral evolution. The data is marginally consistent with a μ = 0.7-0.8 model evolving between t = 6 and 16 in a H_o = 50, q_o = 0 cosmology, but this is not the only possible choice of parameters.

The amplitude of the 4000 Å discontinuity (defined in Bruzual 1983c) has been pointed out by Spinrad (1980) to change systematically with galaxy redshift. More data compiled by this author (Spinrad 1983, private communication) follow the same trend indicated in Fig. 4 of Bruzual (1983c). This trend can be explained if more distant galaxies have more massive stars in the main sequence than nearby ones, as expected for an evolving stellar population.

Oke, Bertola, and Capaccioli (1981) have argued that the observed spectral differences between nearby and distant galaxies are not due to an age effect but are instead the result of observing a larger fraction of the distant galaxies through a fixed-size aperture. Presumably, this would also explain the behavior of the 4000 Å discontinuity. More high quality data are needed before the origin of the observed changes can be definitely established.

(c) Color Evolution

Galaxy colors are expected to change with redshift because of the combined effects of the K-correction and the evolution of the s.e.d. The observations of faint galaxy colors are less uncertain than the direct measurements of the slope of the s.e.d. because the width of broad band filter is typically 300-400 Å, i.e. a filter covers between 100 to 200 channels of a typical spectrophotometer, and hence the signal-to-noise ratio increases proportionally. Moreover, with a photographic plate many galaxies are covered at the same time, and statistically complete samples can be built in reasonable times.

The determination of the redshift of every galaxy in the sample does require of spectrophotometric work. However, accurate redshifts are determined only when the galaxy shows two or more emission lines (even though there are one-emission-line-redshifts in the literature!). The detection of the lines requires shorter integration times than the determination of the continuum level. If it can be established that a group of galaxies are in a cluster, usually the redshift has to be determined for a few ($\sim$ 3.5) of the brightest galaxies in the cluster. Then the photometric properties can be investigated for all the cluster galaxies assuming that all of them are at the same redshift as the brightest ones. Any field galaxy is likely to show colors not in agreement with the cluster galaxy colors (Koo 1981a).

What information can be derived from faint galaxy colors? The first thing to realize is that broad-band fluxes provide us a rough indication of the shape of the spectrum of the emitting source. Using several bands (at least 4) conveniently placed in wavelength we can, in principle, derive as much information from the colors as from the direct s.e.d.'s (Kron 1978, Bruzual and Kron 1980, Koo 1981b, Windhorst, Kron and Koo 1983, Thuan *et al.* 1984).

The behavior in the color-redshift plane of most color systems is very similar (Bruzual 1983c). At low redshifts the dominant effect is the K-correction, which makes the galaxy color redder than the corresponding value for a similar galaxy at z = 0. In order to illustrate these effects in a specific case, the B-V vs. z behavior will be discussed. Fig. 5a shows the behavior of B-V with z for the s.e.d.'s shows in Figs. 1 and 2. The top dashed line in this figure represents the color expected for an elliptical galaxy (s.e.d. as the one in Fig. 1) when observed at reshift z. The bottom dashed line represents the same quantity for the s.e.d. of NGC 4449 (Fig. 2). To obtain the color K-correction the value of the ordinate at z=0 must be subtracted from the curves shown.

The solid lines shown in Fig. 5a correspond to μ-models with the following values of μ: 0.01 (bluest), 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 (reddest) at t_g = 16. For these models Salpeter (1955) IMF:

$$x = 1.35 \ , \qquad 0.08 \leq m \leq 75 \ m_{\odot}$$

was used. To relate time and redshift the cosmology H_o = 50, q_o = 0 was chosen.

The data points shown in this figure correspond to the sample of first ranked cluster galaxies from Kristian *et al.* (1978). These galaxies are expected to be representative of elliptical galaxies at their respective redshift.

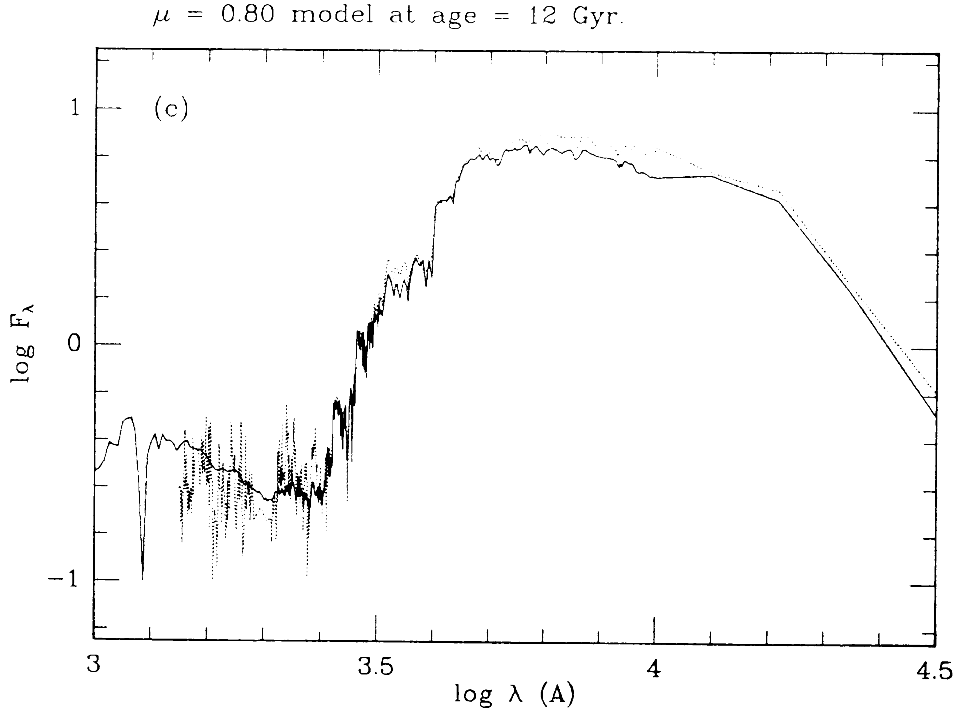

Fig. 3. Comparison of the average s.e.d. for an elliptical galaxy with the s.e.d. for a $\mu = 0.80$ model at $t_g = 12$ Gyr. The Miller and Scalo (1979) IMF was used to build this model s.e.d. The observed s.e.d. is the dotted line.

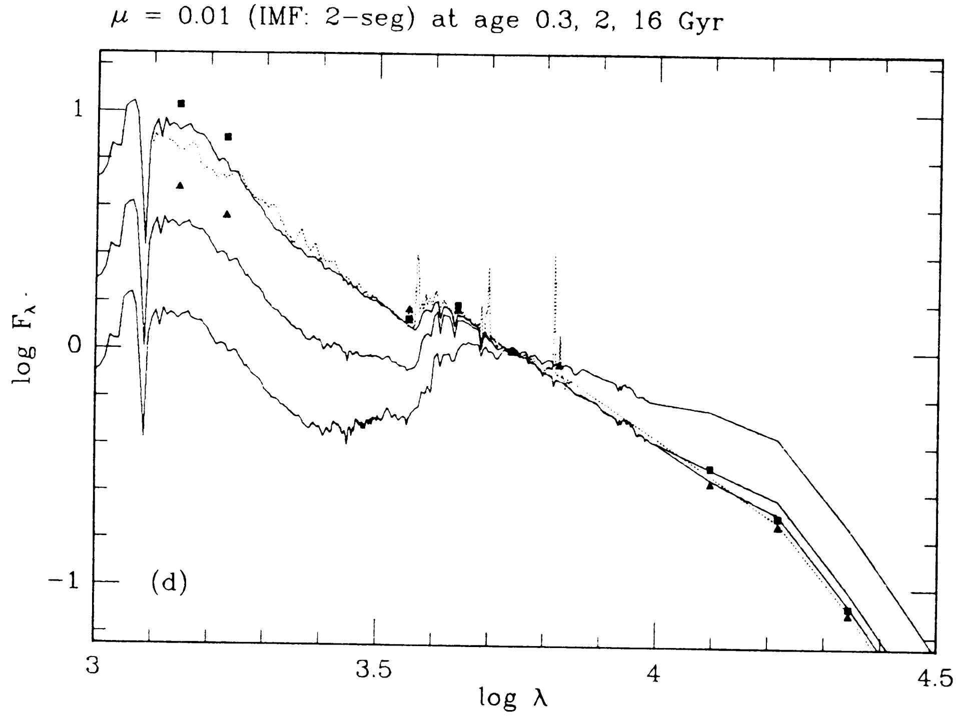

Fig. 4. Comparison of the s.e.d. of NGC 4449 and the model s.e.d. for a $\mu = 0.01$ model at $t_g =$ 0.3, 2, and 16 Gyr (top to bottom in the UV; reverse in the IR) assuming the 2-segment IMF defined in the text. The observed s.e.d. is the dotted line.

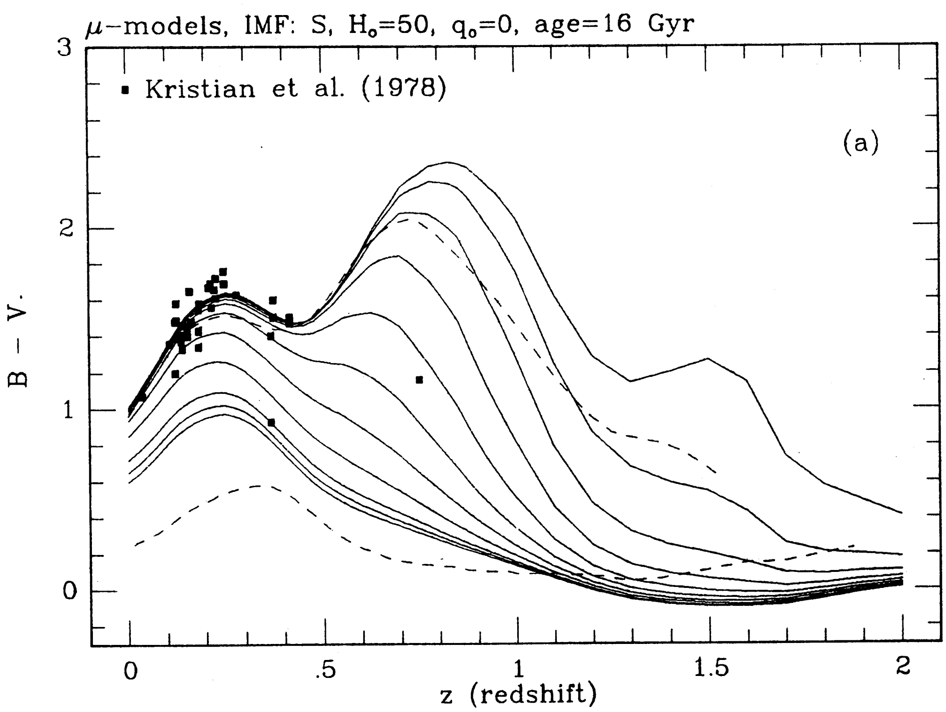

Fig. 5a. Behavior of B-V with redshift for models with the following values of μ: 0.01 (bluest), 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 (reddest) at age t_g = 16 Gyr for the Salpeter IMF and the H_0 = 50, q_0 = 0 cosmology.

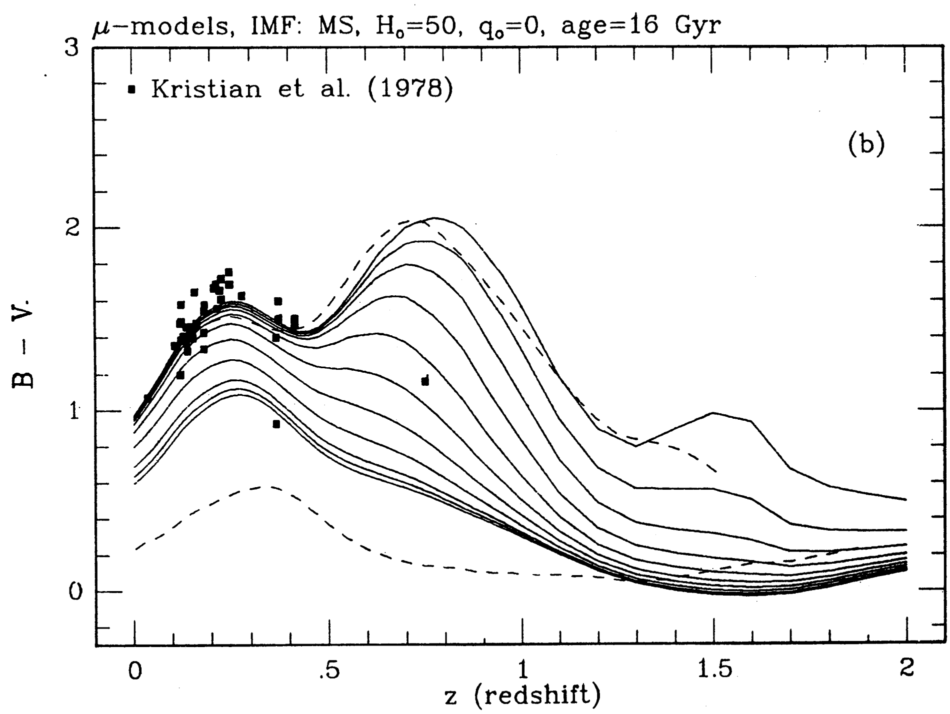

Fig. 5b. Same as (a) but for the Miller and Scalo IMF.

Figure 5b is identical to Fig. 5a in all respects except that in this case Miller and Scalo (1979) IMF:

$x = 0.25$ for $0.08 < m < 1.0\ m_\odot$,

$x = 1.00$ for $1.00 < m < 1.90\ m_\odot$,

$x = 1.30$ for $1.90 < m < 8.00\ m_\odot$,

$x = 2.30$ for $8.00 < m < 2.50\ m_\odot$,

was used. This figure is shown to illustrate the effects of a different IMF in the color behavior.

I would like to point out a difference between these two figures and the corresponding ones in Bruzual (1983c, cf. Fig. 5). The lines marked N.E. in the latter correspond to the K-correction derived from a synthetic c-model s.e.d. at the indicated age and not from an average observed elliptical galaxy s.e.d. Since this model is known to be deficient in UV flux with respect to the observed s.e.d. the model K-corrections are larger than the ones derived from the observed s.e.d. By definition the K-correction must be computed from an observed s.e.d., and the curves shown here should be preferred over the ones shown in Bruzual (1983c).

The following conclusions can be derived from Fig. 5a and 5b.

(a) Most of the data points cluster around the non-evolving or very slowly evolving s.e.d.'s.

(b) A few data points with $z < 0.3$ show colors significantly bluer than the K-corrected color. However, an equally large number of points show colors than are redder than expected from the K-correction. The origin of this red color remains unknown.

(c) The galaxy at $z \sim 0.8$ is significantly bluer than the nearby galaxy, NGC 4486 or NGC 4649, if redshifted by that amount will fall close to this position and this galaxy will still be consistent with a non-evolving s.e.d. (only a brighter one in the UV). Thus it is not straighforward to interpret such a data point as evidence of spectral evolution in galaxies.

(d) The bluest galaxy ($z \sim 0.4$) has the color of a system that will evolve in time into a system significantly bluer than an elliptical galaxy, provided that what we are seeing in this galaxy is normal stellar evolution and continuous star formation. According to the present models such a galaxy will end up at $t = 16$ with $B-V \approx 0.6$, significantly bluer than the average elliptical ($B-V \approx 1$).

The conclusions expressed above rest on the assumptions that star formation takes place in a continuous fashion (μ-model) and that all galaxies are coeval (all assumed to have $t_g = 16$ in Figs. 5a and 5b). However, this is not the only possible interpretation.

Figure 6 shows the B-V vs. z dependence for a c-model ($\tau = 1$) when the galaxy age t_g is assumed to be in the range from 4 (bluest) to 14 Gyr (reddest) in 1 Gyr steps. The Salpeter IMF was used in this case. The vertical segments in the color lines at the bottom of the figure point to the value of the *formation redshift* for the same cosmology as before and the corresponding galaxy age. Thus under the assumption of a spread in galaxy ages it is possible that the bluest galaxies in Kristian *et al.* sample evolve into normal elliptical galaxies. Formation redshifts as low as 0.5 have to be admitted though.

The key fact in the previous arguments is that the bluest galaxies in the sample owe their color to upper main sequence stars that are absent in the reddest galaxies. It is not needed that the whole galaxy has been formed at that z, but that some non-negligible star formation had taken place in the recent past of the system. In Fig. 7 this possibility is explored.

In this figure the c-model ($\tau = 1$) is compared with a $\mu = 0.8$ model at $t_g = 12$ and for the same cosmology as before. For both models the Miller and Scalo IMF was used. The line marked 1 represents the *K-correction* derived from the c-model at $t_g = 12$. Note that for $z > 0.6$ this line starts deviating by a large amount from the real K-correction (that derived from the observed s.e.d. and shown as a dashed line). This behavior is a consequence of the lack of UV flux in the c-model as compared to the observed s.e.d. discussed above. The line marked 3 represents the color behavior for the same c-model when it is allowed to evolve as a function of time. For $z > 1$ the model behavior is markedly bluer than the K-correction. Lines 2 and 4 are equivalent to lines 1 and 3 but for the $\mu = 0.8$ model. The agreement of line 2 and the K-correction reflects the agreement of the model and observed s.e.d. shown in Fig. 1 and 3. The line marked 5 shows the effect in the galaxy color of a second burst of star formation superimposed in the old population of the first burst. The second burst was assumed to start at t = 3 Gyr and to last for τ_2 = 0.025 Gyr. When the massive stars in the second population disappear the model recovers the behavior of the c-model (at z = 0.6). The relative strength of the second burst with respect to the first burst is 0.025 (in mass of material transformed into stars).

For the example of Fig. 7 the second burst was chosen to reproduce the blue point at z $\sim$ 0.8. Similarly, a more recent second burst can be used to reproduce the lower z blue galaxy.

One problem that should always be kept in mind when studying the behavior of galaxy properties with redshift is the physical similarity of the systems under consideration. Many galaxies are selected for spectrophotometric study because of their peculiar blue colors, or another peculiarity such as being optical counterparts of radio sources (Lilly 1983). It would not be surprising that systems in which star formation has taken place in the recent past are over represented in the galaxy samples now available. This star formation may have been triggered by some external event, possibly the same kind of event that is responsible of the radio activity of some of these galaxies. From the present galaxy samples it may be premature to conclude that the blueing of the color at a given z is just due to the fact that at that z all elliptical (red) galaxies are being seen at their early stages of intense star formation (van der Laan and Windhorst 1982, Lilly, Longair and McLean 1983). It may as well be that the selection criteria just work against including the reddest galaxies in the sample, whereas in reality blue and red galaxies may coexist at a given z. Careful study of a complete sample of galaxies is needed before differences in the star formation history of galaxies can be ruled out.

From the previous discussion it is apparent that the interpretation of the colors of single galaxies in terms of the evolving spectrum of an evolving stellar population is not unique, and that physically different evolutionary paths may lead to the same observed colors.

However, if the color vs. z dependence is studied in a complete sample of galaxies (all galaxies brighter than a given magnitude in a volume of space) one hopes that any existing trends in galaxy in galaxy evolution will show up in the color redshift plane. For example, Koo (1981a) has shown that the member galaxies in a cluster at z = 0.54 behave as expected in the color-color plane, and that the cluster galaxies are well separated from the field galaxies in this plane. The complete sample described above should be equivalent to a sequence of clusters and the observed colors in this sample should cover the range of color corresponding to the given range in z.

The compilation of such a sample is a slow process. Windhorst, Kron, and Koo (1983) and Thuan *et al.* (1984) have been working in a deep sample during the last few years. The details of this survey will be published soon by these authors.

The interpretation of Thuan *et al.* results with the help of Bruzual (1983c) evolutionary models leads to the following conclusions:

(a) Weak and strong radio galaxies, and optically selected (radio-quiet) field galaxies cannot be distinguished by their infrared and optical-infrared colors. The colors are probably due to the stellar population and are independent of the radio flux and radio power of the galaxy. Hence any conclusion derived from these data should apply to the evolving stellar populations in galaxies.

(b) A significant fraction of these galaxies (about 60%) show colors that are consistent with the colors of a non-evolving elliptical galaxy s.e.d. or a very slowly evolving ($\mu \sim 0.7$) model s.e.d.

(c) About one third of the galaxies show colors that are much bluer than those expected from a luminous elliptical galaxy. The range of colors covered in this sample seems to be bracketed by the elliptical galaxy colors on the red side, and the colors for NGC 4449 in the blue side.

(d) The range of observed colors seems approximately constant with redshift, in the sense that at all z's red and blue galaxies are observed. This is an interesting result, because one expects (cf. Fig. 5) that in the early phases of galaxy evolution most galaxies should be rather blue. There should be a value of z beyond which the great majority of galaxies should look blue (if it is true that galaxy formation is coeval) and a paucity in the red galaxies should also be noticeable. From the fact that red galaxies are observed at all magnitude levels in the sample one can conclude that up to the depth of the survey (z $\sim$ 0.6) one is still observing galaxies in their slow evolutionary phases, and that the earlier phases, where evolution is

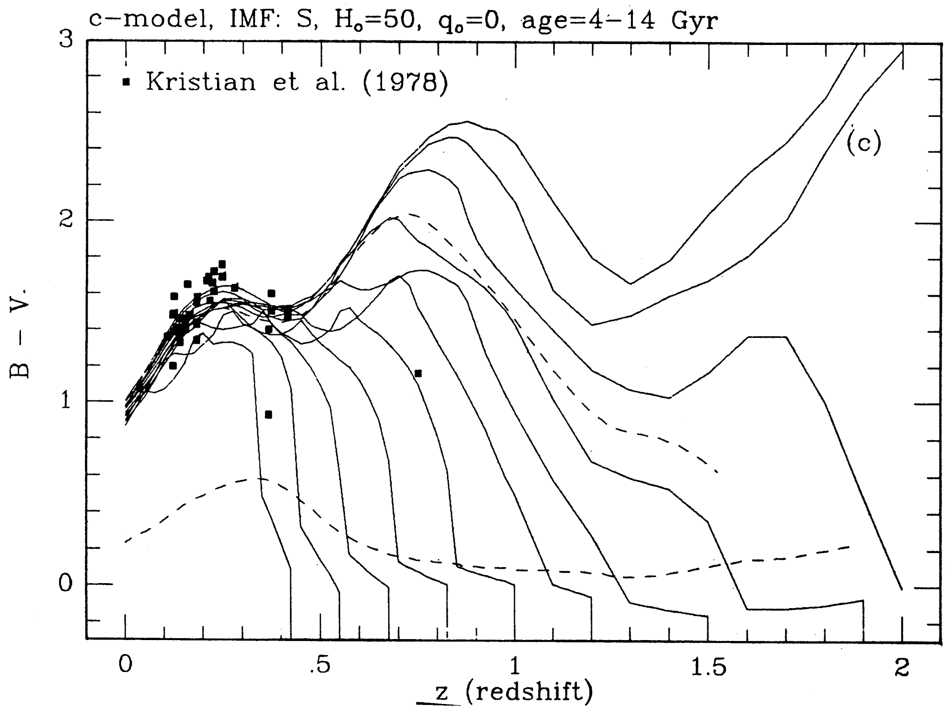

Fig. 6. Behavior of B-V with redshift for a c-model (τ = 1) at t_g = 4 to 14 Gyr in 1 Gyr steps. The Salpeter IMF was used with the same cosmclogy as in Figure 5.

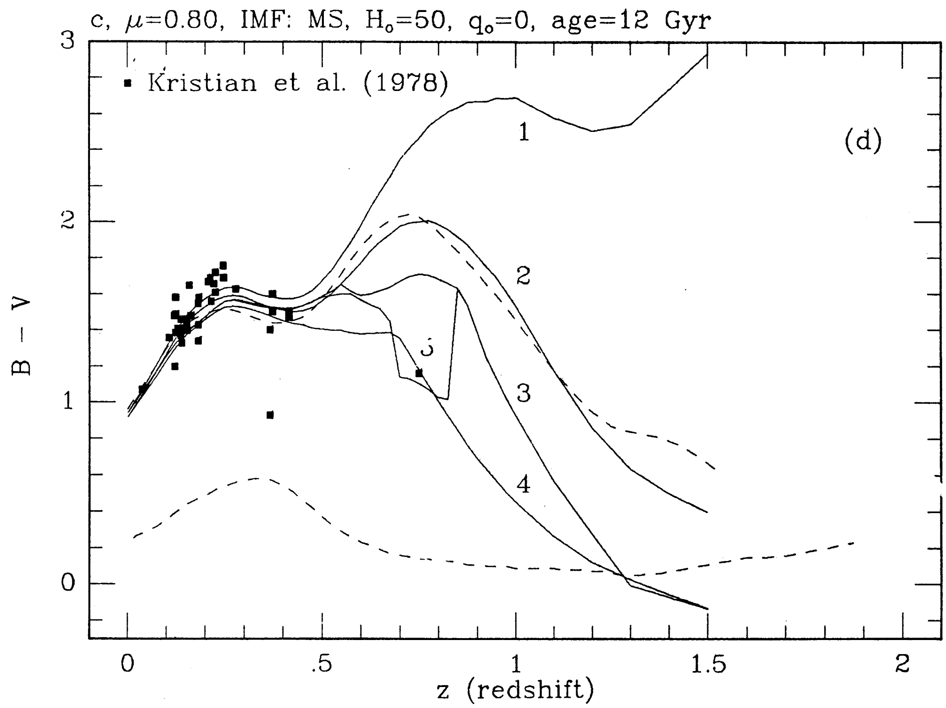

Fig. 7. Behavior of B-V with redshift for the evolving and non-evolving s.e.d.'s of the c and the μ = 0.80 model at t_g = 12 Gyr (see text for more details about this figure). In this figure, as well as in Figures 5 and 6, the dashed lines represent the color K-correction for the average elliptical s.e.d. and for the NGC 4449 s.e.d.

faster and galaxies look bluer, has not yet been detected. If the Typical population in elliptical galaxies was already dominant at $z \sim 0.6$, from an analysis as the one in Fig. 6 one concludes that these galaxies must have formed stars at least at $z \lesssim 1.5$ (for initial burst models) Lower formation redshifts will lead to systems that will look too blue at $z \sim 0.5$ (cf. Fig. 6).

(e) The blue galaxies observed in this sample are most likely lower luminosity ($V > -22$), relatively near ($z \lesssim 0.3$), intermediate and late-type galaxies ($0.01 \leq \mu \leq 0.70$), which will evolve into the corresponding types observed among the nearest galaxies. There are too many of these blue galaxies in the sample to represent transient stages in the evolution of elliptical galaxies.

Infrared colors should, in principle, be considerably better than optical ones as redshift indicators since models predict little sensitivity to evolution (up to $z \sim 1$), morphology, galaxy luminosity, and reddening. Ellis and Allen (1983) showed that some scatter is, however, observed in the J-K color vs. z plane even for carefully chosen optically-selected galaxies at known z. Additional data shown by Ellis (1983) do not improve the situation (cf. his Fig. 9). As Ellis points out it is still possible that observational errors could be underestimated, and many of the published redshifts could possibly be incorrect. Lilly (1983) has also shown infrared color vs. z plots in which the scatter is larger than anticipated.

IV. CONCLUSIONS

In this paper I have presented a summary of our current understanding of the subject of spectral evolution of galaxies. Despite all the observational and theoretical effort than has gone into the subject, one could said that the only safe conclusion that has been established is that some distant galaxies are brighter in the UV than most nearby elliptical galaxies.

However there are reasons to be optimistic. The encouraging results of Koo (1981a) show that faint galaxy colors can be used as redshift indicators. The preliminary results of the deep samples of Koo, Kron, and Windhorst, and Thuan *et al.* indicate that at least the range of colors observed in distant galaxies is understood in terms of non-evolving or slowly evolving stellar populations. The rapid evolution at the early epochs of elliptical galaxy formation (when the upper main sequence was still populated) has not yet been detected.

Most of these conclusions, as well as the ones presented throughout the paper, are only tentative. The reason for this being that the amount of data is very small and the uncertainties large. To establish the validity or not of these results the amount of data has to increase substantially. Fortunately large telescopes are being planned which provided with modern and fast detectors (many of them yet to come) will work towards that aim, and will make this area of research a very profitable one. Hopefully in the next few years many of the questions that still remain will be answered, and many new and interesting questions will arise.

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