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THE RED ENVELOPE AND THE AGE OF THE UNIVERSE

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ABSTRACT. The photometric evolution of old stellar populations is slow in the optical/IR. Consequently, observational error is a strongly limiting factor in the accuracy possible for determining galaxy ages or estimating q_o at high redshifts from indices such as the 4000 Å Break. Existing observations of the red envelope at $z \gtrsim 0.3$ are consistent with a wide range of evolutionary histories. The middle-UV spectral region, $\lambda_{\rm rest} = 2000\text{-}3300$ Å, appears to promise less ambiguous results.

INTRODUCTION

The original motivation for observations of very distant galaxies was to study the large scale structure of the universe and in particular to estimate the deceleration parameter, q_o, which in combination with the Hubble constant, H_o, determines the age of the universe in the Friedmann models. The classical method (Sandage 1962) involves determining the dependence of apparent magnitude on redshift, z. Unfortunately, it is necessary to make a number of significant corrections (*e.g.* for redshift, sampling, aperture, and evolutionary effects) to the magnitude data on objects at $z \gtrsim 0.2$. These have rendered the cosmological problem less tractable than originally hoped (*e.g.* Gunn & Oke 1975, Tinsley 1977, Kristian *et al.* 1978, Spinrad & Djorgovski 1987), and progress toward an unambiguous measure of q_o by these methods has been slow.

As our ability to obtain photometry and spectroscopy of distant systems has improved, an alternative approach has suggested itself—namely to use the *colors* or other spectral characteristics of luminous galaxies viewed at large lookback times to estimate their *ages* and thereby constrain H_o and q_o. The first applications of this method have yielded large values for the age of the galaxies and hence low values of q_o for a given H_o. Hamilton (1985) and Spinrad (1986) claim that the presently fashionable inflationary model, for which $\Omega = 1$ ($q_o = 0.5$), would be excluded given the best current estimates of H_o, which are ≥ 40 km s^{-1} Mpc^{-1}.

While the spectrum/age-dating method is immune to some of the corrections plaguing the $m - z$ method, it is, of course, not without its own difficulties. I want to consider some of those in this paper. The issues are identical to those involved in the question of how well we can judge the *evolutionary state* of galaxies at high redshifts and hence in the controversies over the interpretation of the Butcher-

Oemler effect (*e.g.* Oemler 1986 and many contributions in this conference) and the ages of elliptical galaxies (O'Connell 1986a, Renzini 1986, Pickles 1987 & this conference). These are important problems in their own right, independent of cosmological questions.

AGE-DATING THE RED ENVELOPE

For cosmological applications of the spectum/age-dating method one clearly wants to choose systems which started forming stars at as early an epoch as possible. For technical reasons (*e.g.* O'Connell 1986a) it is also desirable that they *completed* star formation early or at least that star forming activity at more recent epochs was minimal. Now, it is well established that at any redshift up to $z \sim 0.7$ there is a well defined upper boundary or *red envelope* to the color distribution of galaxies. At $z = 0$ this occurs at $(B - V) \sim 1.0$ while at $z \sim 0.3$ it has shifted to $(B - V) \sim 1.7$ in the laboratory frame as a consequence of the K - correction (*e.g.* Kristian *et al.* 1978, Spinrad 1986). There are very few objects located redward of this envelope. At low redshifts, the envelope is occupied by the most luminous E/cD/S0 galaxies. At moderate redshifts, the most luminous objects also tend to fall near the envelope (*e.g.* Butcher *et al.* 1983, Lilly & Gunn 1985) and it is presumed that these are also E/cD/S0's, although morphological data is usually not available. For $z \gtrsim 0.4$ however, brightest cluster members exhibit a wider range of colors (Eisenhardt & Lebovsky 1987; Persson, this conference), and it is not clear whether all of these are E/cD/S0's or how they are related to the red envelope systems.

In the absence of anomalies such as nonthermal radiation, dust, or unusually high metal abundance, it is undoubtedly valid to assume that the objects constituting the red envelope are the *least active* among the sample at a given redshift in terms of star formation over the preceding few Gyr. They are therefore the best systems with which to pursue the cosmological problem. However, to decide whether or not these objects completed star formation at an early epoch and have been completely quiescent since—*i.e.* whether they resemble globular clusters, which have been quiescent for ~ 15 Gyr—requires a careful analysis of their spectral properties. Proximity to the red envelope is not sufficient to guarantee this, as will be clear shortly.

To probe the evolutionary state of any galaxy through integrated light observations one requires: *(i)* accurate data and *(ii)* a robust spectral synthesis technique. The reliability of spectral synthesis techniques is a bone of contention at present (*e.g.* Pickles, this conference), but for the purposes of this section I will *ignore* this and imagine that a perfectly robust technique is available (as it surely will be at some point in the future). I will focus instead on the first requirement and ask: what observational precision is necessary to make unambiguous inferences in this problem?

The properties of the integrated spectrum which are of interest are continuum slopes (or colors), continuum breaks, absorption line strengths, and so forth—which I will refer to collectively as *indices.* Numerous spectral synthesis models for such indices are available in the literature, and it turns out that for a quiescent stellar population which is aging in the absence of new star formation the models indicate their evolution can in most cases be well approximated by the simple relationship

$$Q(\mathrm{mag}) = a + b \log t_{\mathrm{Gyr}}$$

where Q is the index expressed in magnitudes, a and b are constants, and t is the age of the population. This approximation is best for $t \geq 1$ Gyr but is usually adequate for $t \geq 0.1$ Gyr.

It is evident from this expression that spectral indices evolve more rapidly at early times (0.1-1.0 Gyr) than at late times ($t \geq 3$ Gyr). Consequently, unless the coefficient b is large, the photometric evolution of old populations will be *slow*. In fact, b is not large for most optical/IR indices. Taking data from models by Larson & Tinsley (1978) and Rabin (1980), I find the following b's for $(U - V)$, $(B - V)$, and $(V - K)$, respectively: 0.80, 0.33, 0.47 (mags). Individual absorption line indices, *e.g.* Mg I, typically have shallower time dependences than the long-baseline continuum colors.

To illustrate the effects of slow photometric evolution on interpretation of high redshift data consider the case of the "4000 Å Break" index, which is often used as an evolution diagnostic (*e.g.* Bruzual 1983; Hamilton 1985; Spinrad 1986; Gunn, this conference). Values for the standard Break index, $D(4000)$, in old population models with solar abundance and e- folding times for star formation of 0.25 Gyr are given by Hamilton. I have converted these to magnitude form, $d(4000) \equiv 2.5 \log D(4000)$, and find that the b coefficient is 0.37 mag for $t > 3$ Gyr. Not surprisingly, the sensitivity of d to age is comparable to that of $(B - V)$.

This formulation of spectral index evolution may be combined with the look-back/redshift function in any cosmological model to derive the dependence of index on redshift. In Figure 1, I show the resulting $d(4000) - z$ diagram for $H_o = 50$ km s^{-1} Mpc^{-1}, $\Lambda = 0$, and several assumed values of q_o and z_{GF} (the formation redshift). (Note that the d index is measured in the rest frame of the galaxy and is not subject to a K-correction.)

The character of this diagram is governed mainly by the b coefficient. The fact that b is small implies, for example, that the four plotted curves are separated by only 0.11 mag at $z = 0$ despite an age difference from top to bottom of 7.8 Gyr. Changing the value of H_o results in only a zero-point offset to the curves, which amounts to -0.07 mag if $H_o = 75$ km s^{-1} Mpc^{-1} were adopted instead. In any attempt to estimate q_o from such diagrams, one presumes that a good value of H_o would be available from other observations.

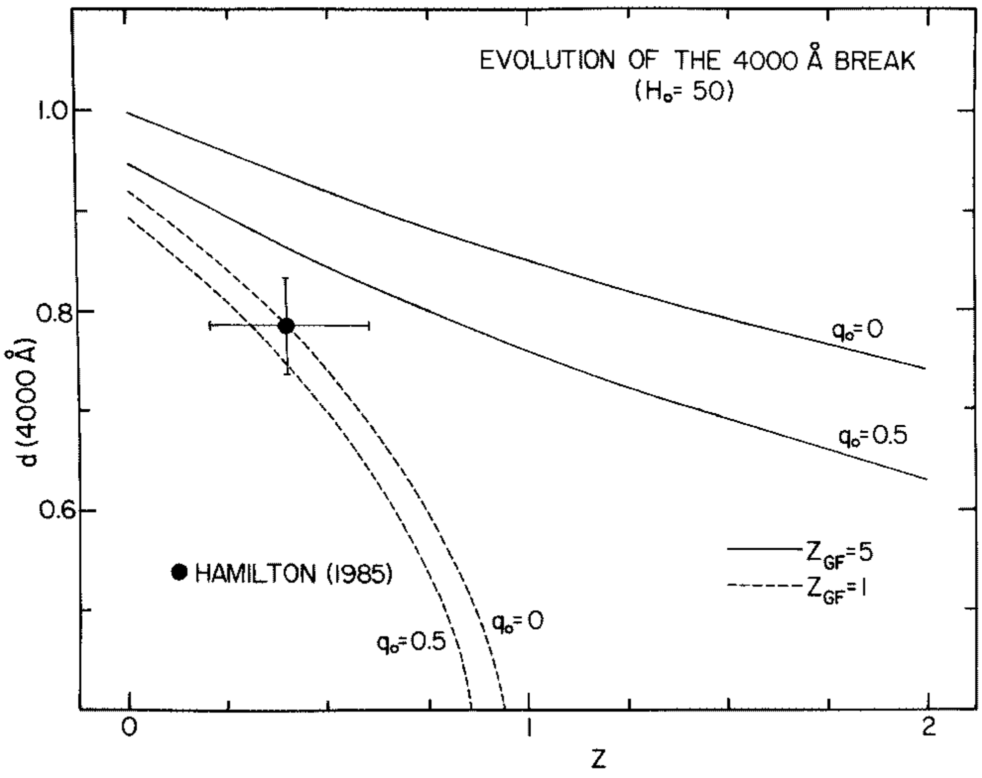

FIGURE 1: The evolution of the 4000 Å Break index (in magnitudes) for two values of q_o and the galaxy formation redshift, z_{GF}. Based on Hamilton's synthetic models, for which $a = 0.55$ and $b = 0.37$, as described in the text. The plotted point is the mean value for Hamilton's red envelope sample; the horizontal bar encompasses 80% of his objects.

Hamilton's data is plotted mainly to illustrate the presently achievable σ_{obs}; however its interpretation is worth a comment. The mean break index shown corresponds to an age of 4.3 Gyr in the context of his $\tau = 0.25$ Gyr model and falls on the $q_o = 0$, $z_{GF} = 1$ curve. Hamilton was unwilling to accept so recent a formation epoch and suggested that his model d indices were too large because of a mismatch in metal abundance. However, his $Z = Z_\odot$ models actually should represent integrated gE light well (Baum *et al.* 1986). Hamilton's data showed no strong trend with z, probably because of selection effects. The mean trend lines of the Spinrad (1986) and Gunn (this conference) samples, however, fall near the $z_{GF} = 1$ curve. No strong conclusions should be drawn, but the properties of the red envelope are not inconsistent with relatively recent formation of E galaxies.

The slopes of the curves depend on q_o but only slightly. This implies that a determination of q_o requires proper modeling of the absolute Q values or, equivalently, *absolute age determinations.* At $z \sim 1$, the $q_o = 0$ and $q_o = 0.5$ curves for $z_{GF} = 5$ are separated by only 0.09 mag, which implies that a 3σ determination of q_o to ± 0.1, for instance, requires a photometric precision of $\sigma_{\rm obs} \sim 0.006$ mag.

This S/N requirement seems well beyond the current state of the art for optical/IR observations. The data point plotted in Figure 1 is from Hamilton's (1985) spectroscopy and represents the mean for 26 faint galaxies, a considerable investment of observing time. For this sample, $\sigma_{\rm obs} = 0.05$ mag., far larger than required for an accurate q_o determination. To put this another way, this $\sigma_{\rm obs}$ corresponds to an age differential of $\pm 30\%$ or a $t(\max)/t(\min)$ ratio of 1.9. Since the dominant contributors to observational error on distant objects are not necessarily photon statistics but instead uncertainties in the sky background, flat-fielding, flux calibration, redshifts, and so forth, this situation is not readily ameliorated simply by using longer integration times.

The conclusion is that, quite apart from uncertainties in synthesis modeling, observational error is a *strongly limiting factor* in the accuracy with which one can age-date the red envelope or obtain q_o values at high redshifts from observations at (restframe) optical/IR wavelengths. In fact, since $\sigma_{\rm obs}$ at $z \sim 0$ is much smaller, Figure 1 suggests that this is better done on local objects than at high z. But at any redshift, one desires indices with larger b coefficients.

THE USEFULNESS OF THE MIDDLE-UV FOR AGE-DATING

Because of the strong dependence of UV flux on stellar temperature, spectral indices in the middle-UV region (2000-3300 Å) have larger b coefficients than the optical/IR indices discussed above. For instance, I find that the index $(m_{25} - V) \equiv -2.5 \log \left[F_\lambda(2500 \text{ Å}) \,/ F_\lambda(5500 \text{ Å}) \right]$ has $b = 3.85$ mag, which is *ten times* larger than for $(B - V)$ or $d(4000)$. Such middle-UV indices therefore promise superior age-dating resolution. They are particularly worth considering for the high redshift problem because the restframe UV is shifted to wavelengths which are readily observable from ground-based observatories if $z \gtrsim 0.5$.

There are difficulties with the middle-UV, however, most of which have to do with our current lack of understanding of this region in composite light. I list some of these below more in the spirit of pointing out interesting astrophysical problems to be solved than as mere technical gremlins:

(i) Galaxies are fainter in the UV than in the visible. Observations by Smith & Cornett (1982) and Burstein *et al.*(1987) indicate that $(m_{25} - V) \sim$ 2-4 mags for nearby E/S0 galaxies. Photometric S/N from source photon statistics will therefore be lower in the UV. Extinction from foreground dust will also be higher. However, the sky background for 3500-6000 Å will be fainter by 2-3 mags than in the near-IR, meaning that restframe UV data for distant objects is subject to less sky noise than restframe visible/IR data. One should compare the S/N resulting from these observational factors with the greatly improved segregation in the UV $Q - z$ diagram. If effects other than source photon statistics dominate the net S/N, then UV brightness may not be a serious limitation.

(ii) E/S0 galaxies contain a still-unidentified hot component which produces significant flux in the far-UV ($\lambda \leq 2000$ Å) region (reviewed in O'Connell 1986a). Its amplitude is apparently correlated with galaxy metal abundance (Burstein *et al.* 1987). I have computed expected $(m_{25}-V)$ colors for old stellar populations without this "UVX" component. When these are compared to the large aperture middle-UV data of Smith & Cornett (1982) or the nuclear *IUE* data of Burstein *et al.*, I find most galaxies exhibit a 1-2 mag excess in $(m_{25}-V)$ regardless of the age assigned to the old population. My models assumed $Z = Z_{\odot}$, and since metal abundances in E galaxies remain above solar to relatively large radii, this excess is unlikely to be a metallicity effect. It is reasonable to attribute it to the long-wavelength tail of the UVX component. The implication is that an understanding of the UVX component is important to interpreting middle-UV as well as far-UV data. If the UVX component is directly linked to the old population (*e.g.* post-AGB stars), which I think is likely, this problem will be less serious than if it is wholly independent (*e.g.* recently formed massive stars).

(iii) Smith & Cornett (1982) performed large aperture broad-band photometry on a number of Virgo E/S0 galaxies in the middle-UV and found for the S0's a strong color-luminosity dependence, $(m_{25}-V) \sim -0.70V + 11.4$, where V is the apparent V magnitude of the galaxy. The brightest E galaxies appeared *not* to follow this same relation. The photometry has relatively low S/N, but it does represent the largest homogeneous sample of integrated UV data on E/S0's, and it raises the spectre of significant luminosity *and* morphological effects on middle-UV colors.

(iv) Middle-UV spectra will be sensitive to metal abundance as a consequence of strong metallic line blanketing. Good estimates of blanketing effects are not available yet, but based on Kurucz's (1979) model atmosphere calculations for solar-type stars, I estimate $\delta(m_{25}-V) \sim 1.6 \log Z/Z_{\odot}$. This, again, is a relatively strong effect which must be properly calibrated in synthesis models. Good methods for determining abundances in high redshift systems are also evidently essential.

(v) Finally, most data on distant systems will be for their integrated light, and comparison to nearby galaxies therefore requires proper UV-color/aperture corrections. One expects significant gradients from the outward decline of metal abundance (*e.g.* Baum *et al.* 1986), but the available sample of UV photometry is too small and inhomogeneous to study aperture effects. Unfortunately, the *Hubble Space Telescope* is not well suited to obtaining off-nuclear UV surface photometry of E/S0 galaxies, leaving the three UV instruments of the *ASTRO* Spacelab missions as the only likely important contributors to our understanding of aperture effects for the next 5 years or beyond.

Does this long and sobering list of problem areas remove the middle-UV from consideration for studying the evolutionary state of distant galaxies? I think not, because most of these arise from the *increased sensitivity* of the UV to precisely those parameters we want to measure—namely turnoff temperatures and metal abundances—and the complicating factors must be considered in the context of the increased amplitude of all such photometric effects in the UV. Some of these issues—*e.g.* the nature of the UVX components—should be settled quickly by *HST* and *ASTRO*. Others are no more serious and, given the relative amplitude of the effects, may be less serious than comparable difficulties and ambiguities in the visible region (*e.g.* the problem of separating evolved from main sequence starlight).

To close on two positive notes, first Ellis (this conference) has already found evidence at $\lambda_{\rm rest} \sim 2500$ Å of recent star formation in cluster E/S0's at moderate lookbacks which is not detectable at visible wavelengths. This will serve as an important probe of the "post-starburst" or "E+A" phenomenon. Second, absorption line features in the middle-UV are very sensitive to the age of the stellar population (see Figure 2), meaning that moderate resolution UV spectroscopy of nearby systems with *HST* and *ASTRO* should rapidly improve our understanding of this spectral region.

LATE EVOLUTION OF ELLIPTICAL GALAXIES

The nature of the red envelope is also a key element in the debate over the evolutionary history of E galaxies. There is a substantial body of evidence which indicates that significant star formation in nearby E/S0 galaxies continued until as recently as 5-8 Gyr ago. Since this has been covered at length in recent reviews (Burstein 1985; O'Connell 1986a, 1986b, 1987; Pickles 1987) I will not discuss it here. This is a controversial conclusion, however, and the existence of the red envelope at higher redshifts is often cited by critics as being inconsistent with this interpretation.

It should be clear from the preceding why the red envelope does not invalidate this late-evolution picture for E galaxies. First, the rapid evolution of color during the first 3 Gyr after star formation ceases implies that the ancestors of local E/S0's could readily have made the transition from the "blue population" at moderate redshifts to the $z = 0$ red envelope in the available time period. Such "quenched" evolutionary paths might be expected if mergers or other strong environmental interactions are common; examples were published some time ago by Tinsley (1980, Fig. 1). Second, the slow color evolution after 3 Gyr coupled with photometric errors and residual uncertainties in the evolutionary models implies that the red envelope at moderate redshifts is consistent with a *wide range* of evolutionary interpretations. Bruzual (1986, Fig. 6) and Wyse (1985) were able to fit the red envelope data for $z \lesssim 0.5$ with models having ages at $z = 0$ of 6-16 Gyr, depending on modeling assumptions and the metal abundance assigned. The envelope at $z \sim 0.5$ was fit by Bruzual's models with an age at that epoch of $\gtrsim 3$ Gyr. Overall, I think there is nothing in the available high redshift data which constitutes a serious challenge to the late-evolution interpretation of nearby E's, and there is a good deal which is consistent with it (see, for example, the discussion in the caption for Figure 1).

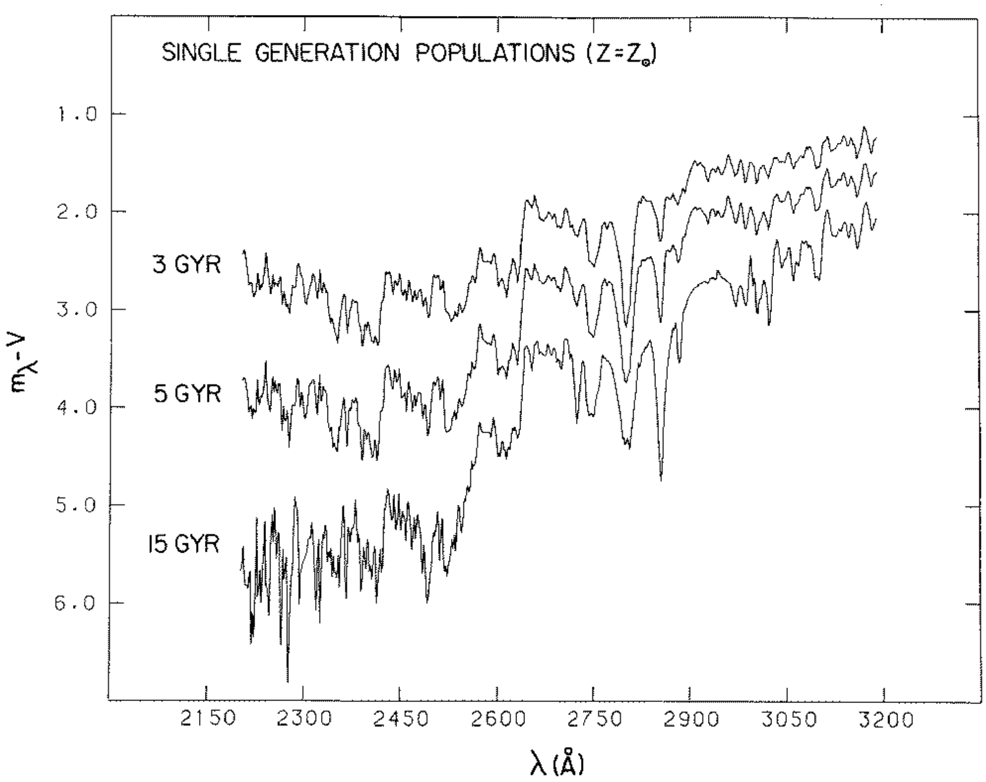

FIGURE 2: Synthetic middle-UV spectra for single generation, old populations with $Z = Z_\odot$, based on the *IUE UV Spectral Atlas.* All spectra are normalized at 5500 Å. Ages are indicated. Note the significant changes in both continuum level and line strengths with age. The optical/IR spectrum is much less sensitive to age.

CONCLUSION

The slow evolution of optical/IR photometric indices in old stellar populations places heavy demands on both observational precision and synthesis modeling techniques if the goal is to obtain a good estimate of q_o or the ages of high redshift galaxies. For indices such as the 4000 Å Break, one requires $\sigma_{\rm obs} \lesssim 0.01$ mag, and this seems beyond the current state of the art. Consequently, the existing data on the red envelope is consistent with a wide range of evolutionary histories and, in particular, with the late-evolution interpretation of nearby E's. The restframe middle-UV promises much improved age-dating of old populations if a number of technical and astrophysical complications can be successfully addressed. None of these appears intractable. It remains to be seen whether such methods of estimating q_o, based on stellar evolution timescales, will be competitive with results based on nuclear chronometers (Fowler 1987).

Finally, I think it is important to have a better understanding of the physical sources of photometric dispersion in luminous red galaxies for $z \lesssim 0.5$ (*e.g.* Wilkinson & Oke 1978) and to establish the nature of the reddest outriders on the color distribution.

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REFERENCES

Baum, W.A., Thomsen, B., and Morgan, B.L. 1986. *Ap. J.*, **301**, 83.

Bruzual, A.G. 1983. *Ap. J.*, **273**, 105.

Bruzual, A.G. 1986. In *Spectral Evolution of Galaxies*, eds. C. Chisoi and A. Renzini (Dordrecht: Reidel), p. 263.

Burstein, D. 1985. *P.A.S.P.*, **97**, 89.

Burstein, D., Bertola, F., Buson, L., Faber, S., and Lauer, T. 1987. In preparation.

Butcher, H., Oemler, A., and Wells, D.C. 1983. *Ap. J. Suppl.*, **52**, 183.

Eisenhardt, P.R.M., and Lebofsky, M.J. 1987. *Ap. J.*, **316**, 70.

Fowler, W.A. 1987. *Q.J.R.A.S.*, **28**, 87.

Gunn, J.E., and Oke, J.B. 1975. *Ap. J.* , **195**, 255.

Hamilton, D. 1985. *Ap. J.*, **297**, 371.

Kristian, J., Sandage, A., and Westphal, J.A. 1978. *Ap. J.*, **221**, 383.

Kurucz, R.L. 1979. *Ap. J. Supp.*, **40**, 1.

Larson, R.B., and Tinsley, B.M. 1978. *Ap. J.*, **219**, 46.

Lilly, S.J., and Gunn, J.E. 1985. *M.N.R.A.S.*, **217**, 551.

O'Connell, R.W. 1986a. In *Stellar Populations*, eds. C. Norman, A. Renzini, and M. Tosi (Cambridge: Cambridge Univ. Press), p. 167.

O'Connell, R.W. 1986b. In *Spectral Evolution of Galaxies* , eds. C. Chisoi and A. Renzini (Dordrecht: Reidel), p. 321.

O'Connell, R.W. 1987. In *Starbursts and Galaxy Evolution*, eds. T. Montmerle and T. Thuan (Paris: Editions Frontieres), in press.

Oemler, A. 1986. In *Stellar Populations*, eds. C. Norman, A. Renzini, and M. Tosi (Cambridge: Cambridge Univ. Press), p. 197.

Pickles, A.J. 1987. In *Structure and Dynamics of Elliptical Galaxies (IAU Symposium No. 127)* , ed. T. de Zeeuw (Dordrecht: Reidel), in press.

Rabin, D.M. 1980. Ph. D. Thesis, California Institute of Technology.

Renzini, A. 1986. In *Stellar Populations*, eds. C. Norman, A. Renzini, and M. Tosi (Cambridge: Cambridge Univ. Press), p. 213.

Sandage, A.R. 1962. *Ap. J.*, **136**, 319.

Smith, A.M., and Cornett, R.H. 1982. *Ap. J.*, **261**, 1.

Spinrad, H. 1986. *P.A.S.P.*, **98**, 269.

Spinrad, H., and Djorgovski, S. 1987. In *Observational Cosmology (IAU Symposium No. 124)*, ed. G. Burbidge (Dordrecht: Reidel), in press.

Tinsley, B.M. 1977. *Ap. J.*, **211**, 621.

Tinsley, B.M. 1980. *Ap. J.*, **241**, 41.

Wilkinson, A., and Oke, J.B. 1978. *Ap. J.*, **220**, 376.

Wyse, R.F.G. 1985. *Ap. J.*, **299**, 593.