THE UV EMISSION OF ELLIPTICAL GALAXIES

LAURA GREGGIO\textsuperscript{1,2} AND ALVIO RENZINI\textsuperscript{3}
\textsuperscript{1}Universit"{a}ts Sternwarte M"{u}nchen, Scheinerstr. 1, D-81679 M"{u}nchen, Germany
\textsuperscript{2}Dipartimento di Astronomia di Bologna, Via Zamboni 33, I-40126 Bologna, Italy
\textsuperscript{3}ESO, Karl-Schwarzschild-Str. 2, D-85748 Garching b. M"{u}nchen, Germany

ABSTRACT. Observational as well as theoretical developments subsequent to 1990 concerning the origin of the ultraviolet emission of elliptical galaxies are reviewed and discussed. In particular, successes and failures of an extensive set of predictions contained in Greggio & Renzini (1990) are discussed in the light of these developments. Strong support to the preferred hot horizontal branch and AGB–manqué scenario for the origin of the UV emission has come from UIT, HUT and HST observations. However, the UV sensitivity of such space telescopes has proved insufficient to detect the predicted fade away effect of the UV upturn with redshift, that we consider the ultimate check for this scenario. Some serendipitous discoveries prompted by studies of the UV upturn are also mentioned.

1. Introduction

At optical wavelengths the spectral energy distribution (SED) of elliptical galaxies falls precipitously shortward of the 4000 ˚A break, hence the discovery of the UV-rising branch came as one of the most unexpected results of the first UV satellites. The general prejudice was that ellipticals contained exclusively old and cool stellar populations, similar to metal rich galactic globulars, albeit even more metal rich. However, a few bright very hot stars were known to be globular cluster members, and the presence of similar objects in ellipticals had been suggested before the discovery of their UV rising branch (Minkowski & Osterbrock 1959; Hills 1971), but this knowledge was not widely spread. The first UV spectra of ellipticals and bulges of spirals showed instead that shortward of ∼ 2300 ˚A the flux was increasing with decreasing wavelength. A fundamental contribution to this subject is due to Burstein et al. (1988), who collected and organized all the relevant information from IUE observations. The three main results of this study were: 1) all studied ellipticals have detectable UV flux, 2) their (1550–V) color spans a range of ≈ 2.5 mag, and 3) it is strongly correlated with the Mg\textsubscript{2} index. Hence, the ratio of the UV to the optical emission varies by ∼ an order of magnitude, and this ratio appears to increase with average metallicity (Z), assuming that the Mg\textsubscript{2} index traces Z.

The presence of young, massive (hence hot) stars in ellipticals was soon entertained in order to account for the observed UV radiation. On the other hand, low mass stars do evolve through hot evolutionary phases at the end of their life, and some UV radiation is naturally expected to arise also from purely old stellar populations. Greggio & Renzini
(1990, hereinafter GR90) explored a variety of possible candidates produced by the evolution of low mass stars, both single and in binary systems. In particular, in GR90 we concentrated on the possibility of producing hot stars in \( \sim 10 \) Gyr old stellar systems, which could account for the observed level of the UV-to-optical flux ratio, and (qualitatively) of the correlation with metallicity. We used simple energetic arguments, based on the fuel consumption theorem (Renzini and Buzzoni 1986), to translate the observed level of the UV rising branch into specific requirements for the candidate stars responsible for the UV emission. In this paper we first summarize the main results of GR90, and then review and discuss both the observational and the theoretical developments following 1990.

2. The Theoretical Background

The argument in GR90 goes as follows. The ultraviolet SED as measured from IUE is consistent with the Rayleigh-Jeans tail of a black body curve of temperature higher than \( \sim 25000 \) K. In order to estimate the ratio of UV to total flux an assumption on the typical temperature of the hot component is necessary. For example, for NGC 4649, one of the most powerful ellipticals, \( L_{UV}/L_T \) is in the range from 0.014 to 0.021, for \( 20000 < T_{eff} < 40000 \) K.

For single age and single metallicity populations of single stars (simple stellar populations, SSPs), the contribution to the total bolometric light of stars in the generic \( j \)-th post-MS evolutionary phase is

\[
L_j/L_T \approx 9.75 \times 10^{10} B(t) F_j(M_{TO}) \tag{1}
\]

where \( B(t) \) is the specific evolutionary flux, i.e. the number of stars evolving through the turnoff and beyond per year per solar luminosity of the parent population (in units of \( \# \, * \, yr^{-1} L_\odot^{-1} \)), and \( F_j \) is the amount of fuel burned during the phase \( j \) by stars of initial mass equal to the turn-off mass (\( M_{TO} \)) at the age \( t \) of the population. The fuel \( F_j \) is expressed in \( M_\odot \) of equivalent hydrogen, i.e. \( F_j = \Delta M_j^H + 0.1 \Delta M_j^{He} \), where \( \Delta M_j^H \) and \( \Delta M_j^{He} \) are respectively the mass of hydrogen and helium burned during the phase \( j \). For old SSPs \( B(t) \approx 2.2 \times 10^{-11} \) stars \( L_\odot^{-1} \, yr^{-1} \), almost independent of composition and age (cf. Fig. 1 in Renzini 1998). Going one step further, equation (1) can be generalized to a collection of SSPs (composite stellar population, CSP), e.g. one exhibiting a narrow range of ages but a wide metallicity distribution, that GR90 adopted as a fair description of the stellar content of ellipticals. To this end, suffice to substitute \( F_j(M_{TO}) \) with the fuel averaged over the metallicity distribution \( < F_j >_Z \). Thus, for old stellar populations with a metallicity distribution the following simple relation holds:

\[
L_j/L_T \approx 2 \times < F_j(M_{TO}) >_Z \tag{2}
\]

This equation was the main tool used in GR90 to evaluate various kinds of stars as potential contributors to the UV rising branch in ellipticals.

From the observational requirement \( L_{UV}/L_T \approx 0.02 \), equation (2) immediately indicates that the hot stars responsible for the UV emission from giant elliptical galaxies
should burn at least $\sim 0.01 M_\odot$ of equivalent hydrogen. As already mentioned, the range in $(1550 - V)$ colors spanned by ellipticals is consistent with $L_{UV}/L_T$ varying by one order of magnitude. Accordingly, the fuel burned by the candidate hot stars, averaged over the metallicity distribution, should increase from $\simeq 0.001$ to $\simeq 0.01 M_\odot$ when the average metallicity of the CSP increases. GR90 listed four candidates, which are naturally produced in the advanced stages of the evolution of single stars:

(i) Post AGB stars (P–AGB), i.e. stars which leave the AGB after the first thermal pulse, and reach $T_{\text{eff}} \gtrsim 100,000$ K before approaching the white dwarf (WD) cooling sequence. This is certainly the most common channel to reach the final WD stage. Typical luminosity $\sim 1000 L_\odot$.

(ii) Post Early AGB stars (P–EAGB), i.e. stars leaving the AGB before the first thermal pulse, as most of their hydrogen envelope is lost before. Typical luminosity $< \sim 1000 L_\odot$.

(iii) Hot HB stars (HHB), sometimes also called Extreme HB (EHB) stars, i.e. stars which spend the core helium burning phase at high temperatures, and whose subsequent evolution (shell helium burning phase) also takes place at high temperature (AGB–manqué). Typical luminosity $\sim 20 L_\odot$ for HHB, few $100 L_\odot$ for AGB–manqué.

(iv) Post RGB stars (P–RGB), i.e. stars which fail helium ignition because they loose their envelope while climbing on the RGB. Typical luminosity $\lesssim 1000 L_\odot$.

The first three channels eventually produce carbon-oxygen WDs, the last one helium WDs. Fig. 1 shows schematically the evolutionary paths corresponding to channels (i), (ii) and (iii). Also shown are the limiting magnitudes for objects in M31 reached with 1.5 h exposures with WFPC2 in two Wood’s filters. It appears evident how difficult it is to detect individual HHB stars at this distance.

A stellar population of given metallicity will certainly produce stars evolving through channels ii), iii) and iv) provided it becomes sufficiently old. However, the age at which this happens cannot be accurately predicted. A model star of given initial mass will evolve through one of the four channels above depending on the wind mass loss rate efficiency ($\eta$). For $\eta$ below a critical value it will go through the P–AGB, and for larger and larger values of $\eta$ it will switch to the P–EAGB, HHB+AGB–manqué, and finally to the P–RGB track. As illustrated in GR90, this whole range of possibilities is realized by varying the mass loss rate parameter $\eta$ by just $\sim$ a factor of two, i.e. by an amount vastly smaller than any observational uncertainty affecting empirical RGB and AGB mass loss rates. This leaves ample freedom to theoreticians.

All available evolutionary calculations indicated (and still indicate) that P–AGB stars burn less than $\sim 0.003 M_\odot$, and P–RGB objects even less. This allowed GR90 to conclude that stars in these evolutionary phases could play only a minor role in the production of the UV upturn. More promising appeared the P–EAGB, with $F_{\text{P–EAGB}}$ up to $\simeq 0.025 M_\odot$, and the HHB and their AGB–manqué progeny, burning in total $\sim 0.5 M_\odot$ of helium (equivalent to $\sim 0.05 M_\odot$ of hydrogen). If all stars were to go through the HHB+AGB–manqué channel $\sim 5$ times more UV radiation would be produced than needed to account for the $\sim 2\%$ of the total luminosity emitted in the UV, as in the (1550 - $V$) bluest galaxies. Thus, a relatively small fraction ($\simeq 20\%$) of the stellar population in ellipticals needed to evolve through channel (iii) in order to fit the observations. The trend of the (1550–$V$) color increasing with $Z$ could then be understood if a larger fraction of the population was evolving through channel (iii) at higher average
metallicity. Such a trend could be accomplished in either of two ways: 1) with a modest increase with metallicity of the mass loss rate parameter \( \eta \), or 2) with the helium abundance \( (Y) \) increasing with metallicity \( (Z) \). Indeed, at fixed age and metallicity, a larger \( Y \) corresponds to a smaller envelope mass for the star evolving along the RGB, so that it is easier to produce objects (ii) to (iv). Moreover, higher helium \textit{per se} favors higher effective temperatures, e.g. during the HB phase (cf. Sweigart & Gross 1976). In essence, which of the 4 channels is realized depends on how the mass loss rate and \( Y \) scale with \( Z \), both parameters \( \eta(Z) \) and \( \Delta Y/\Delta Z \) being poorly known observationally. At the same time, hosting stellar populations with a metallicity spread, ellipticals should be inhabited by all four kind of objects, though in different proportions.

The main conclusions in GR90 can be summarized as follows:

(i) P–AGB stars, these hot low mass objects necessarily present in ellipticals do not provide enough UV flux to account for the level of the UV rising branch in the most powerful galaxies.

(ii) The UV upturn in old stellar populations could be accounted for only by the presence of P–EAGB and HHB stars, with up to \( \sim 20\% \) of all evolving stars venturing through...
these channels.

(iii) The production of these stars at high $Z$, as seemed implied by the $(1550 - V) - \text{Mg}_2$ correlation, was possible within the uncertainties affecting the empirical determination of $\eta(Z)$ and $\Delta Y/\Delta Z$, which are inputs to stellar evolution theory.

(iv) Whatever mechanism is responsible for the production of these stars (i.e. mass loss or $\Delta Y/\Delta Z$), one expects that all possible candidates are present in ellipticals, though in different proportions.

(v) If the hot stars responsible for the UV emission in the most powerful ellipticals were P−EAGB and HHB objects, the UV rising branch should fade away rapidly with increasing redshift, possibly already disappearing at redshifts as low as $z \gtrsim 0.2$. This was a direct consequence of the sensitivity of the effective temperature of HB stars on the envelope mass at helium ignition.

GR90 paid less attention at the temperature distribution of the stars evolving through the various channels, but pointed out the overwhelming difficulty of predicting such distribution, that from the theoretical point of view depends on a number of arbitrary functions. We felt indeed that detailed spectral synthesis modelling was not worth the effort, while the only possible firm conclusions could be reached with very simple arguments. However, it was mentioned that the 2300 Å dip in the SED requires a gap in the temperature distribution between HHB stars and the remaining, cool HB stars. No explanation for the existence of this gap was given in GR90. Moreover, if a continuity exists between HHB and P−RGB stars, then one may expect HHB stars to extend all the way to the helium main sequence, hence to fairly high effective temperatures ($T_{\text{eff}} \sim 50,000$ K). In other words, this scenario would most naturally produce a fairly wide temperature distribution of UV emitters. It was also speculated that a sizable fraction of HHB and their AGB−manqué progeny could be helium stars, suffice indeed fairly modest mass loss rates ($10^{-10} - 10^{-9} M_{\odot} \text{yr}^{-1}$) for these stars to lose completely their hydrogen envelope. This possibility was predicted to be subject to observational test, as in this case the UV upturn should have exhibited some Wolf-Rayet, WN−like features, such as low or absent CIV and Lyman lines, and strong HeII and NV.

3. UV Observations Beyond IUE

In 1990 much of the available information on the UV upturn came from IUE, and it has been organized by Burstein et al. (1988). Later, most of the observational novelties came from UIT, HUT, and HST. Direct UV imaging became possible, as well as spectroscopy down to the Lyman continuum.

3.1. UIT and HST Imaging of Nearby Spheroids

UIT and HST imaging have definitely ruled out massive stars as the origin of the UV upturn in M32, the bulge of M31, as well as in NGC 1399, one of the UV most powerful ellipticals (O’Connell et al. 1992; King et al. 1992; Bertola et al. 1995a; Cole et al. 1998).

Extremely blue, low mass stars have been directly imaged in the bulge of M31 and in M32 by HST (King et al. 1992; Bertola et al. 1995a; Brown et al. 1998). Although none of these objects is a massive elliptical, they follow the $(1550 - V) - \text{Mg}_2$ correlation
which characterizes all quiescent Es. The King et al. and Bertola et al. data were taken with the pre-Costar FOC. The first group obtained images of a central field in M31 through a filter centered at $\lambda = 1750$ Å, resolving more than 100 objects. Based on their measurement of the UV magnitudes, and on an upper limit to their $(1750 - B)$ color, the authors concluded that the resolved stars in the F175W images are P–AGB stars; and, by comparing with the IUE flux from the same area, that these stars account for only a fraction ($\sim 20\%$) of the total flux at 1750 Å.

Bertola et al. (1995a) obtained images of M31, M32 and NGC 205 through the combined UV filters F150W and F130LP, resolving 81, 10 and 78 stars in the three objects respectively. The point like sources in NGC 205 were interpreted as young OB stars (as already known from ground-based observations), while the luminosity of the sources in M31 and M32 suggests that these are P–AGB stars. By comparing with IUE data, the authors conclude that the resolved P–AGB objects can account for the total UV flux in the case of M32, while for M31 $\sim 50\%$ of the UV flux comes from an unresolved background.

Therefore, both groups conclude that the UV light in the bulge of M31 likely comes from the combination of P–AGB stars and fainter objects, which appear as an unresolved diffuse background on the HST image. The different value derived by the two groups for the contribution of the resolved sources results from the different assumptions on the sensitivity calibration of the pre-COSTAR FOC, and on the uncertainties on the red leak through the UV filters. At any rate, the conclusions from both groups confirmed the prediction of GR90, i.e. the population of hot stars in old stellar systems is composite, with contribution from P–AGB stars bright enough to be individually detected in nearby spheroids, and fainter sources such as P–EAGB and HHB+AGB–manqué stars as faint as $\sim 20L_\odot$ (hence below detection threshold). Concerning M32, the low level of its UV upturn is in agreement with the notion that the UV sources in this galaxy should just be P–AGB stars, with very few stars – if any – going through the (ii)-(iii) channels.

UV color gradients have also been detected in a few objects (O Connell et al. 1992). With the exception of M32, UV colors become redder with increasing radius, probably tracing the Mg$_2$ gradients. The UV light appears diffuse, but more concentrated than the visual light, in agreement with the expectation that it is produced by the higher Z stars, preferentially found in the central regions (see also Brown et al. 1998).

Post-Costar FOC photometry of M32 and M31 has been recently obtained by Brown et al. (1998) in two UV filters, namely F275W and F175W. Again, many point like sources are resolved in these images: 433 stars in M31 and 138 in M32 down to $m_{F275W} = 25.5$ mag and $m_{F175W} = 24.5$ mag. Brown et al. (1998) show that the pre-COSTAR FOC calibrations were likely in severe error, basically leading to an overestimate of the intrinsic UV flux from the sources. As a result, the resolved stars in Brown et al. are interpreted as AGB–manqué objects, the bright progeny of HHB stars. Again, the cumulative flux from the resolved stars accounts for only a fraction ($< 20\%$) of the total IUE flux. Although still affected by some uncertainty, in particular a possible systematic underestimate of the flux in the F275W filter at the 0.3 mag level, the photometry by Brown et al. (1998) is in reasonable agreement with the expectations from IUE and HUT spectra.

The interpretation of the nature of the resolved sources in Brown et al. (1998) rests
essentially upon the characteristic of the luminosity functions (LF) in the two UV filters. There appears to be an increasing number of objects towards fainter magnitudes, a trend which is not present in the P–AGB tracks of Vassiliadis & Wood (1994) to which the empirical LF was compared. These tracks peak instead at magnitudes for which there are virtually no stars observed at all. Brown et al. conclude that the bulk (∼95%) of all stars do indeed go through the P–AGB channel, but the mass of the P–AGB stars is in excess of 0.63M⊙, for which the P–AGB timescale is so short to be consistent with the observed LF. However, such a high value of the P–AGB mass would imply the existence of a prominent and very bright population of AGB stars, for which there is no evidence in the bulge of M31 (Renzini 1998). Moreover, this population would produce an enormous amount of energy (∼0.15M⊙ of fuel would be burned on the AGB), hence leading to optical–infrared colors at variance with the observed ones. In our opinion, the Brown et al. LF demonstrates that the Vassiliadis & Wood P–AGB tracks are inapplicable to the case of the M31 bulge. These tracks are based on the assumption that the transition from the AGB to the planetary nebula stage takes place on a nuclear time scale, being controlled by the burning of the residual envelope mass. For the low values of the P–AGB mass expected in an old stellar population (∼0.55M⊙) this transition time is indeed very long (∼10^5 yr), and a sizable number of hot P–AGB stars would have been observed, lying along the nearly horizontal track in the upper part of Fig. 1. However, one knows from galactic globular clusters that the transition is instead much faster, taking place either on a mass-loss time scale, or even more probably on a thermal time scale (Kaeufl, Renzini, & Stanghellini 1993, and references therein). We conclude that the observed LF is likely due to the combination of the low-mass P–AGB channel (∼95% of the total stellar evolutionary flux), with the transition to high temperatures taking place on a thermal time scale, plus P–EAGB and/or the HHB+AGB-manqué objects for the residual stellar evolutionary flux (∼5% of the total).

An apparently puzzling result of the Brown et al. study is that the LFs of the UV stars in M31 and M32 look similar in shape, in spite of the strong difference in the level of the UV upturn in these two galaxies. According to Brown et al. the fraction of the total evolutionary flux that has to go through the non P–AGB channel is 2% and 0.5% respectively in the bulge of M31 and in M32. Hence, the similarity of the two LFs comes from both being dominated by P–AGB stars that do not evolve on a nuclear time scale through their transition from the AGB to high temperatures.

In 1993 FOC imaging in four UV bands was obtained of the central regions of the ellipticals NGC 1399 and NGC 4552 and of the bulge of the NGC 2681 spiral (PI F. Bertola). The aim was to study the spatial structure of the UV emission, checking for color gradients and if any patchiness existed due to star formation. No such patchiness was found neither strong color gradients, but instead NGC 4552 and NGC 2681 showed a central, unresolved, point-like source (Bertola et al. 1995b). To our surprise, we found that the point-like source in NGC 4552 had changed its brightness by a factor ∼ 7±1.5 in the F342W band, compared to a previous FOC image taken in 1991: a central flare had been discovered, possibly due to a red giant having been tidally stripped by a massive central black hole (Renzini et al. 1995). Subsequent, post-COSTAR FOC imaging and FOS spectroscopy confirmed that the central source is a variable mini-AGN, possibly the faintest known AGN, with broad (FWHM ≃ 3000 km s⁻¹) emission lines (Cappellari...
et al. 1998). While trying to better understand the UV upturn, we had serendipitously found yet another way of gathering information on the central black hole demography in galaxies.

3.2. HUT Spectroscopy of the UV Upturn

Extending the observed spectral range down to the Lyman limit HUT has detected the maximum in the UV spectral energy distribution (Ferguson et al. 1991). To date, HUT data for 8 early type objects, including the bulge of M31, have been collected (Ferguson & Davidsen 1993; Brown, Ferguson & Davidsen 1995; Brown et al. 1997). In all studied objects, the UV rising branch appears to have a turn-over at $\lambda \approx 1000$ Å, which indicates that the bulk of the radiation comes from moderately hot stars, with temperatures in the range 20000–25000 K (Brown et al. 1995). Assuming that this is the characteristic spectral energy distribution in the UV for giant ellipticals, like NGC 4649, we obtain a better estimate for the ratio $L_{UV}/L_T$ of $\simeq 0.015$, which translates into $< F_\lambda >_2 \simeq 0.007$ for the hot stars inhabiting the most powerful ellipticals.

Since the UV SED has a minimum around 2300 Å, a large contribution from stars with intermediate temperatures, say $\approx 10000$ K, is excluded. Thus the bulk of the UV emission comes from stars in a narrow range of temperatures. This is an important constraint for the astrophysically plausible evolutionary paths that can account for the UV rising branch phenomenon. For example, an even distribution of stars on the HB like in the globular cluster M3, corresponds to a spectrum flatter than observed in ellipticals, due to the similar contribution from stars in the wide effective temperature range (see e.g. Nesci & Perola 1985, Ferguson 1995).

Another important characteristic of the HUT spectra of early type systems is the fact that they are composite: when removing from the observed spectrum the theoretical contribution of HHB star, according to their complete evolution from the ZAHB to the WD final stage, some residual flux at the shorter wavelengths is left (Ferguson and Davidsen 1993; Brown et al. 1997). The best fits to the SED of all the studied objects are obtained with contributions from both HHB and P–AGB evolutionary tracks. Based on their detailed modelling, Brown et al. (1997) conclude that approximately 10% of the total stellar population should go through the HHB channel of evolution in NGC 1399, one of the strongest UV emitters. This is in very good agreement with the predictions of the fuel consumption theorem: for a two components CSP, with 90% of the stars evolving through the P–AGB channel and the remaining 10% going through the HHB evolution, the average fuel burned in the hot evolutionary phases is:

$$< F_\lambda > = 0.9 \times F_{P-AGB} + 0.1 \times F_{H-HB} \quad (3)$$

Adopting $F_{P-AGB} = 0.003 \, M_\odot$ and $F_{H-HB} = 0.05 \, M_\odot$ (see Sect. 2) one gets $< F_\lambda > = 0.0077$, close indeed to the estimate above.

All of the 8 objects in the Brown et al. sample seem to require some contribution from HHB stars, in different proportions. This does not come unexpected, since their Mg$_2$ indices range from 0.31 to 0.36, which puts them among the high average metallicity objects. Brown et al. (1995) also claimed that, within their sample, a larger fraction of stars evolve through the HHB channel in the stronger Mg$_2$ galaxies. Modelling the UV
spectra, they derive the stellar evolutionary flux through the HHB plus AGB–manqué track which is needed to account for the observed UV emission. The ratio between this evolutionary flux and that of the total stellar population sampled by the HUT aperture appears to be nicely correlated with the $\text{Mg}_2$ index of the parent galaxy. The value of this ratio is model dependent, and somewhat different figures are obtained in the more detailed computations in Brown et al. (1997). Nevertheless, judging from their tables, the general trend seems confirmed. Thus, it can be concluded that galaxies with $\text{Mg}_2$ indices in excess of $\sim 0.3$ very likely host HHB stars in their nuclei. Only a small fraction of the population need to go through this extreme evolutionary channel to account for the observed UV fluxes, varying from $\sim 1$ to $\sim 10\%$ for galaxies with $\text{Mg}_2$ ranging from 0.3 to 0.36. These results are clearly consistent with the expectations from GR90.

The low S/N in the HUT spectra prevents accurate determinations of abundances. The absorption features seem however to indicate a low metallicity in the stellar atmospheres of the stars mainly contributing the UV emission: $Z_{\text{atm}} = 0.1Z_\odot$ (Brown et al 1997). This would imply that the UV rising branch phenomenon is not directly related to the presence of high $Z$ stars, and the correlation between the $(1550 - V)$ color and $\text{Mg}_2$ index has to find a different explanation (Park & Lee 1997, see below) from what proposed in GR90. Alternatively, $Z_{\text{atm}}$ is not representative of the true metallicity of the hot stars in ellipticals, as heavy elements may diffuse out of the atmospheres of HHB stars (Brown et al. 1997). A more firm result of the abundance analysis is the lack of CIV as would be expected if massive stars were responsible for the UV emission. However, HUT spectra show also strong $\text{Ly}\beta$ and $\text{Ly}\gamma$ lines, indicating that the vast majority of HHB and AGB–manqué do not lose their hydrogen envelope, and do not become WN-like helium stars. This means that average mass loss rates during these phases must be lower than $\sim 10^{-10}$ and $\sim 10^{-9} M_\odot \text{yr}^{-1}$, respectively.

3.3. Attempts at Detecting the Evolution with redshift of the UV Upturn

One crucial prediction of GR90 concerned the evolution with redshift of the UV upturn. If due to a combination of P-EAGB and HHB+AGB–manqué stars, the UV upturn should fade away already at fairly low redshift, see for example the realization by Barbaro, Bertola, & Burstein (1992). To check this prediction two Cycle-I HST projects were implemented (PIs R. Windhorst and A. Renzini, respectively). FOS spectra of $z = 0.1 - 0.6$ elliptical galaxies selected for being either weak radiogalaxies and/or cluster members were obtained. They all showed a strong UV upturn, which at first sight appeared to be in clear conflict with the prediction. However, it soon turned out that a similarly strong UV upturn was also shown by the FOS spectrum of an innocent G2V star, which certainly did not have it on its own. While searching for the vanishing UV upturn of ellipticals the red-scattered light problem of FOS was discovered instead (Windhorst et al. 1994). This lead to a novel approach to the calibration of FOS – and lately of ESO instruments for the VLT – which makes more use of first physical principles, and less recourse to least square fits (Bushouse, Rosa, & Müller 1995; Rosa 1997; Ballester & Rosa 1997).

The FOS scattered light problem had the effect of reducing dramatically the S/N ratio for UV observations of high-$z$ ellipticals, and therefore attempts at detecting the
vanishing upturn effect moved to WFPC2, now equipped with Wood’s filters. A first attempt was made by a group including R. Gilmozzi, E. Held, R. Viezzer and ourselves. WFPC2 images of the cluster Abell 895 ($z = 0.37$) were obtained through the Wood’s filter F218W, and through the F555W and F814W filters. No detectable flux from cluster ellipticals was found in a coadded 10,000 second integration through the F218W filter. The result is shown in Fig. 2 for the brightest cluster member (reproduced from Renzini 1996), with the $3\sigma$ upper limit falling disappointingly on top of the expected upturn if such galaxies had the same rest frame $(1550 - V)$ color of the local elliptical NGC 4649.

Similarly disappointing was the result of an analogous experiment by Buson et al. (1998), who imaged the Abell 851 cluster ($z = 0.41$) through the F218W and F702W filters (corresponding to $\sim$ the rest frame $(1550 - V)$ color). Again, the F218W data are not deep enough to detect the cluster ellipticals even if they were to maintain the same rest frame $(1550 - V)$ color of the bluest ellipticals at zero redshift.

The failures of these attempts has to be ascribed to the low sensitivity of WFPC2 when used in conjunction with Wood’s filters (that indeed we nicknamed wood’s filters). An alternative approach has been recently pursued by Brown et al. (1998) for a sample
of ellipticals in the $z = 0.375$ cluster A370. The combination of two long-pass filters of FOC (F130LP and F370LP) has allowed them to isolate the contribution of the emission shortward of $\sim 2700 \, \text{Å}$ in the rest frame, hence sampling the UV upturn. Surprisingly, no appreciable evolution compared to nearby ellipticals has been detected, and Brown et al. conclude that this result excludes some models of the upturn, while others are still acceptable provided that the bulk of stars in these galaxies formed at $z \gtrsim 4$.

More observations are needed to study in detail the evolution of the UV rising branch with increasing redshift, and to derive informations on the nature and the age of the UV bright stars. Since FOS and GHRS have been removed from HST, STIS may now offer a better chance to detect the vanishing UV upturn effect.

4. Theoretical Modelling

4.1. Stellar Evolutionary Sequences

In 1990 only a handful of P–AGB, P–EAGB, and HHB+AGB–manqué evolutionary sequences existed in the literature. In the last decade a large effort has been devoted to construct extensive sets of evolutionary tracks, primarily with the aim of understanding the UV upturn phenomenon. Hundreds of stellar evolutionary sequences for low mass stars, with up to super solar metallicities and helium abundances have been computed to isolate the range of parameters which produce P–EAGB and HHB objects (e.g. Castellani & Tornambé 1991; Horch, Demarque & Pinsoneault 1992; Castellani, Limongi & Tornambé 1992, 1995; Dorman, Rood and O’Connell 1993, hereinafter DRO93; Fagotto et al. 1994a,b,c; Yi, Demarque & Kim 1997a). Basically, the overall evolutionary picture illustrated in GR90 has been confirmed. The average temperature at which the helium burning occurs is essentially controlled by the envelope mass of the stars at helium ignition, being hotter the lower the envelope mass. High values of the helium abundance favor the production of hot helium burners, and widen the range of envelope masses for which this condition is satisfied. According to DRO93, for $Z = Z_\odot$ stellar models with HB envelope masses $M_{\text{env}}^{\text{HB}} \lesssim 0.05 \, M_\odot$ evolve either as P–EAGB or as HHB and AGB–manqué. This critical value for the envelope mass increases with the helium abundance (see also Yi et al. 1997a), reaching values as high as 0.15 $M_\odot$ for $(Y, Z) = (0.45, 0.06)$. It follows that at high $(Y, Z)$ the condition on the envelope mass necessary to produce hot stars is more easily met.

Two interesting aspects of the evolution of low mass stars have been disclosed, which were not considered in GR90: 1) for high $Z$ and especially $Y$, the evolution of HB stars presents a pronounced dichotomy, with some stars starting the evolution on the red side of the HB, spending there a fraction of their HB phase, and then after zipping to high temperatures where they burn the rest of their fuel (Horch et al. 1992, but see also Sweigart & Gross 1976); and 2) for high assumed mass loss rates some stars peel off the RGB and experience their core helium flash at high effective temperatures (Castellani & Castellani 1993; D’Cruz et al. 1996).

The systematics with $Y$ and $Z$ of the post RGB evolution can be appreciated in DRO93 and Yi et al. (1997a): up to $\approx Z_\odot$, the dependence of the ZAHB $T_{\text{eff}}$ on $M_{\text{env}}^{\text{HB}}$ is relatively mild, and a flat distribution of envelope masses maps into an even distribution
in $\log T_{\text{eff}}$ of stars on the HB. Subsequent evolution remains confined in the red (in the blue) for the more massive (less massive) HB objects, while the intermediate HB (IHB) stars evolve along wide redward/blueward loops, thereby providing intermediate temperature objects. Correspondingly, for $Z \lesssim Z_\odot$, it is relatively difficult to produce the 2300 Å minimum in the SED. However, as the metallicity increases, the evolution of the HB objects tends to become more skewed either towards the red, or to the blue. The effect is very strong for large values of the $\Delta Y/\Delta Z$ parameter. At $(Y, Z) = (0.46, 0.06)$ the IHB objects virtually disappear, and the bulk of stars are either redder than $\log T_{\text{eff}} \simeq 3.7$ or bluer than $\log T_{\text{eff}} \simeq 4.2$ (see Figures 2 and 3 in DRO93). This behavior may help producing the 2300 Å minimum in the SED.

As illustrated in the introduction, when the mass loss parameter $\eta$ is sufficiently large, the evolution on the RGB is aborted before the core mass has grown enough to trigger the central helium flash. In GR90 it was assumed that in this case further evolution would just take the model star to the (helium) white dwarf stage. Actual computations in this $\eta$ range show, instead, that there are models which succeed in igniting helium after departing from the RGB, either while crossing the HRD, or during the subsequent cooling phase towards the WD stage (Castellani & Castellani 1993). Thus, there is a mass range (or a $\eta$ range) for which the helium core flash occurs in the hot region of the HRD (hot helium flashers, in D’Cruz et al. 1996 nomenclature). Subsequent evolution of these objects (hereinafter HHeF) is the same as for HHB star, with a very low envelope mass. If they exist, the HHeF have the minimum envelope mass that HB stars can have, hence naturally defining the hot end of the horizontal branch. Stars with more massive envelopes will ignite helium at the tip of the RGB, to appear on the ZAHB with lower $T_{\text{eff}}$. Stars less massive than the HHeF will fail helium ignition, thus becoming helium WDs. At super solar metallicites, HHeF are produced for $\eta \gtrsim 0.7$, which is $\sim 2$ times larger than the value which fits the properties of the HB in globular clusters (Castellani, Degl’Innocenti and Pulone 1995). After helium ignition, the HHeF are found on the ZAHB at $\log T_{\text{eff}} \sim 4.4$ for supersolar $Z$, which seems to be the maximum possible temperature for HB models (Castellani, Degl’Innocenti and Pulone 1995).

4.2. Synthetic UV Upturns

Inspired by the $(1550 - V) - \text{Mg}_2$ correlation most authors have explored under which conditions HHB and related stars are produced in metal rich and super metal rich populations.

Dorman, O’Connell and Rood (1995, hereinafter DOR95) assume the mass loss on the RGB as principal actor in originating the UV rising branch. Two are the main points which support this picture: (1) the presence of extended HB in the CMD of globular clusters, which require a spread in RGB mass loss by $\sim 30\%$ among stars within the same cluster; and (2) the population of hot subdwarfs in the solar vicinity, which shows that at $\sim$ solar metallicity HHB stars and their progeny can occasionally be produced. Thus, in DOR95 view, the hot stars in ellipticals are (moderately) old, $\sim$ solar metallicity objects which happen to loose 2-3 times more mass than the average Reimers rate. Questioning the real significance of the Mg$_2$ index as a metallicity indicator, DOR95 generically ascribe the origin of the correlation $(1550 - V) - \text{Mg}_2$ to either an age or a
metallicity spread among ellipticals. However, no attempt is made to explore the effect of a metallicity distribution on the UV SED of ellipticals. If a large dispersion of the mass loss rate applies to all Z components, it seems difficult to avoid a sizeable contribution of IHB stars in the UV spectral range.

In Tantalo et al. (1996) models HHB stars are produced at high Z basically because a large $\Delta Y/\Delta Z$ is assumed. These authors construct self consistent chemo-spectro-photometric models for the ellipticals, which thus contain a metallicity distribution as computed from the chemical evolution. The final integrated properties of the models depend not only on the assumptions on the parameters governing the stellar evolution (e.g. the mass loss), but also on those important for the chemical evolution (i.e. star formation rate, IMF, stellar yield, depth of the galactic potential, supernova feedback, galactic winds etc.). Tantalo et al. most massive galaxy models present a strong UV upturn developing as early as 5.6 Gyr. This value of the age is extremely sensitive to the specific choice of the parameters $\eta = 0.45$ and $\Delta Y/\Delta Z = 2.5$, which cause the SSP model at $Z = 0.1$ to produce HHB stars already at 5.6 Gyr. On the other hand, all other SSP models in Tantalo et al. grid (with $Z < 0.1$) produce HHB stars only for ages in excess of $\sim 12$ Gyr. Therefore, the UV properties of the composite model also depend critically on the precise population of the highest metallicity bin (see also Yi, Demarque & Oemler 1998).

Finally, Yi, Demarque & Oemler (1997b,1998) propose a model in which all the relevant parameters are allowed to vary while searching for a best fit. They finally favour a positive (but moderate) $\Delta Y/\Delta Z (=2-3)$, a modest trend of $\eta$ with metallicity (ranging from $\sim 0.5$ to $\sim 0.7$–1 for $Z$ ranging from 0.02 $Z_{\odot}$ to $\gtrsim Z_{\odot}$); a mass dispersion of the HB of $\sim 0.06 M_{\odot}$ (calibrated on GC's properties); and a metallicity distribution, as suggested by chemical evolution models. With these prescriptions, Yi et al. (1998) reach a reasonable fit with the observations, at ages $\gtrsim 10$ Gyr. The fit is better when adopting the Z distribution from infall models, as opposed to closed box models. Indeed, in the latter case too much flux is produced in the mid-UV, due to the broad distribution of HB temperatures of metal poor stars.

While in all the above attempts the UV emission arises from stars in the high-$Z$ tail of the metallicity distribution, Lee (1994) and Park and Lee (1997) maintain that the UV flux originates from the emission of metal poor stars. Considering that the stellar populations in galaxies are characterized by a metallicity distribution, they explore the possibility that the optical light comes from the high $Z$ and the UV light come from the low $Z$ components. The relatively low strength of absorption features in the UV-rising branch mentioned in Section 3.2 is in agreement with this picture. The trend of increasing ($\text{UV} - V$) color with increasing Mg$_2$ (hence $<Z>$) would have an indirect origin, resulting from the brighter ellipticals (with stronger Mg$_2$ indices) being older than the fainter ones, as it may be expected in some cosmological simulations.

However, in the Park and Lee model, ages as old as of $\sim 20$ Gyr are needed to produce a UV output such as that of giant ellipticals, which looks uncomfortably too old. Another problem comes from the strongest UV upturns being shown by galaxies with Mg$_2 \gtrsim 0.3$, which cannot have a major metal poor component, as the metallicity distribution should be trimmed below $Z \approx 0.5 Z_{\odot}$ (Greggio 1997). Thus the low $Z$ tail may not be present in the central regions of the most powerful ellipticals (see also
Moreover, as already noticed, it is more difficult to low-$Z$ populations to produce the 2300 Å minimum in the SED, as the $T_{\text{eff}}$ of HB stars is a mild function of the envelope mass. Indeed, the $(1500 - 2500)$ color of the UV rising branch in ellipticals is systematically bluer than in metal poor globular clusters (DOR95). This shows that the average temperature of the hot stars in ellipticals is higher than the average temperature of HB stars in GCs. Only high $(Y, Z)$ models seem to reach blue enough colors (DOR95, Yi et al. 1995, 1998). Finally, we notice that two metal rich globular clusters in the Galactic bulge have been found to host a sizable population of HHB stars (Rich et al. 1997). This has shown that it is indeed possible to produce numerous HHB stars at $Z \sim Z_\odot$, although this may be due to some yet unidentified dynamical process in these particular clusters.

To summarize, most of the theoretical work has just shown quantitatively, in a detailed level, that the options are equivalent: hot stars are produced at high metallicities in old stellar populations if $\Delta Y / \Delta Z$ is large and/or if the mass loss rate moderately increases with metallicity. Which combination of the two effects is at work remains unclear. As we will discuss later, high $Y$ in combination with high $Z$ could be a necessary ingredient in order to avoid too much light in the mid-UV from IHB stars.

5. Discussion and Conclusions

In summary, the current observational evidences that need to be explained include:

- In those ellipticals with the strongest UV upturns $L_{\text{UV}} / L_T \simeq 0.015$.
- The UV SED requires a small temperature range for the hot stars in the nuclei of ellipticals, peaking at $\sim 25,000$ K.
- Among ellipticals with $\text{Mg}_2 \gtrsim 0.3$, the fraction of hot evolved objects going through the HHB channel of evolution varies sizeably, possibly ranging from $\sim 1\%$ to $\sim 10\%$ for $\text{Mg}_2$ increasing from 0.3 to 0.36.
- The shape of the LF of the UV bright stars is similar in M32 and in the bulge of M31. In both galaxies resolved stars account for only of a small fraction of the UV flux.

In this section we discuss the hints on the hot stars in ellipticals from these observational evidences.

5.1. On the hot stars in ellipticals and their origin

Thanks to the HUT spectra reaching shorter wavelengths compared to IUE, a smaller $L_{\text{UV}} / L_T$ is derived, hence a smaller average fuel consumption $< F_{\text{UV}} >_Z$ is required for the hot stars in the most powerful ellipticals, compared to GR90 estimates. However the average fuel consumption remains much larger than what provided by P–AGB stars, and the best candidates hot stars remain P–EAGB and/or HHB+AGB–manqué objects. HHB stars and their progeny tend to be favored essentially because their $F_{\text{UV}}$ is larger than the required $< F_j >_Z$, so only a (small) fraction of the stellar evolutionary flux
has to go through a very hot helium burning stage. Besides, P–EAGB stars are likely to be distributed over the whole $T_{\text{eff}}$ range from $\sim 5000$ to $\sim 70000$ K (see tracks in Castellani and Tornambè 1991), thus providing too much flux both in the mid-UV and in the most extreme UV spectral range.

If the bulk of hot stars in giant Es are HHB + AGB–manqué, some $\sim 10\%$ of the evolving population in the UV brightest ellipticals has to evolve through channel (iii) (see Section 2). This constrains the combination of the parameters $\eta$ and $\Delta Y/\Delta Z$, plus all the parameters which play a role in determining the metallicity distribution in the central regions of the most powerful ellipticals, in particular its high metallicity tail.

Can we learn something on these parameters from the UV SED? As repeatedly noticed here, the observations require that the HHB stars are characterized by a narrow range of $M_{\text{env}}^{\text{HB}}$. In this respect, stellar populations of high metallicities, possibly coupled with large helium abundances, are favored. This stems from an observational argument, since the SEDs of galactic (low $Z$) globulars with extended HBs tend to be flatter than those typical of giant ellipticals. At the same $(1500 - V)$ color (i.e. for the same average $F_{1500}$), the $(1500 - 2500)$ color of GCs are redder than those of giant ellipticals, with only high $Z$ SSP models matching the $(1500 - 2500)$ color (DOR95, Yi et al. 1995, 1998). There is also a theoretical argument in favor of the high $Z$ hypothesis, based on the shape of the relation between $T_{\text{eff}}^{\text{HB}}$ and $M_{\text{env}}^{\text{HB}}$ of HB stars. As $M_{\text{env}}^{\text{HB}}$ decreases $T_{\text{eff}}^{\text{HB}}$ keeps low until a threshold value is reached, after which the relation becomes extremely steep (cf. Fig. 3.1 in Renzini 1977). As a consequence there is a very narrow range of $M_{\text{env}}^{\text{HB}}$ which corresponds to intermediate effective temperatures. Perhaps more importantly, at high metallicites HB stars appears to exhibit a bimodal behavior, with most of the HB (as well as the subsequent shell helium burning stage) being spent either at high or low $T_{\text{eff}}$, virtually avoiding the intermediate regime (see tracks in DRO93). This tendency is reinforced when high $Y$ combines with high $Z$ (Yi et al. 1997b).

In conclusion, the presence of the 2300 Å minimum and the relatively steep slope of the UV SED in ellipticals speak in favor of high $Z$ and $Y$ HHB stars and their progeny. At this point we notice that the strong Mg$_2$ index in the nuclei of giant Es requires that the $Z$ distribution has a small (if any) component at $Z < \sim 0.5 Z_{\odot}$ (Casuso et al. 1996, Greggio 1997). The SED in the UV offers another argument in support of this picture (see also Bressan, Chiosi & Fagotto 1994; Tantalo et al. 1996).

Turning now to the question of producing HHB stars at $Z \geq Z_{\odot}$ in less than a Hubble time, an enhancement of the mass loss rate parameter over the value which fits the GCs properties ($\eta_{\text{GC}}$) seems difficult to avoid. At low $\Delta Y/\Delta Z$ D’Cruz et al. (1996) require an enhancement of a factor 2–3; at $\Delta Y/\Delta Z=2–3$ Yi et al. require an enhancement of a factor $\sim 2$. It’s interesting to notice that, due to this large values of $\eta$, a small mass loss dispersion easily produces the hot helium flashers (see section 3). This class of objects naturally provides an upper limit to the $T_{\text{eff}}$ distribution on the HB (Castellani & Castellani 1993), offering an elegant solution to the problem of why the SED of giant ellipticals shows the turnover at $\lambda \approx 1000$ Å. Indeed, if the HB were populated down to the helium MS, stars would be distributed all the way up to $T_{\text{eff}} \sim 50000$ and beyond, hence producing a hard UV spectrum shortward of Ly$\alpha$, which is not observed.

Thus, the hot stars in the nuclei of giant Es are likely to be objects in the helium burning phase which happened to undergo a particularly heavy mass loss while on the
RGB. Their large Z and Y would produce an evolution confined in a narrow range of effective temperatures. The hot edge of this range would be populated by objects which (due to mass loss) failed helium ignition on the RGB, but succeeded later during the evolution towards the WD stage. These stars would belong to the high-Z tail of the distribution in the GR90 picture, or, alternatively, to the high mass loss tail of the distribution of stars around $\sim Z_\odot$ (DOR95). In the first case, the mass loss parameter $\eta$ should increase with the metallicity; in the second a large dispersion of $\eta$ at $Z\sim Z_\odot$ is needed. The first option more naturally accounts for the $(1550-V)$ vs Mg$_2$ correlation, which we are going to consider next.

Finally, we attach a great significance to the fact that the bulk of the UV emission in M31 bulge and M32 comes from objects which are fainter than the detection threshold with FOC. Indeed, this leaves little alternative to HHB stars as the main UV producers (cf. Fig. 1).

5.2. On the $(UV-V) - Mg_2$ correlation

Among the various possibilities, the CSP in the nuclei of Es with Mg$_2 \gtrsim 0.3$ can be modeled by a family of closed box models, provided they are pre-enriched to $Z \sim Z_\odot$ (Greggio 1997). In these models, the metallicity distribution is $f(Z) \propto \exp(-Z/y)$, with $Z$ varying between a minimum value $Z_m$ ($\sim 0.5 Z_\odot$), and a maximum value $Z_M$. Here $y$ is the yield as defined by Tinsley (1980). Since Mg$_2$ is measured in the optical, where low Z stars have more weight, its value is very sensitive to $Z_m$. The UV flux, instead, would be more sensitive to $Z_M$, if generated by stars in the high-Z tail of the distribution. Therefore, the $(UV-V) - Mg_2$ correlation requires that $Z_m$ and $Z_M$ are well correlated, e.g. they both increase with galaxy mass (luminosity), which seems plausible. If HHB stars are produced only above a threshold metallicity at the present age of the stellar populations in ellipticals, then the $(UV-V) - Mg_2$ correlation can result from the metallicity distribution shifting to higher and higher values in galaxies with higher and higher Mg$_2$ (GR90).

As for the galaxies with Mg$_2 \lesssim 0.3$, there are very few of them in the Burstein et al sample, and they define a correlation with a different slope. From the Mg$_2$ index one expects their metallicity distribution to be shifted to lower values, and thus it would be interesting to know whether their UV SED allows for a larger contribution from low Z stars (i.e. with intermediate temperatures, hence leading to flatter UV upturns). To date this problem has not been quantitatively investigated.

5.3. The Evolution with Redshift Holds the Key

The detection of the redshift evolution of the UV upturn remains perhaps the most attractive opportunity for the future. By detecting the effect we could in fact catch two birds with one stone. If indeed the UV upturn fades away at $z \approx 0.3 \pm 0.1$, this will represent the decisive test for the HHB+AGB–manqué origin of the upturn in $z \approx 0$ ellipticals. Moreover, the empirical determination of the derivative $d(UV-V)/dz$ (hence of $d(UV-V)/dt$) for galaxies of given value of the central velocity dispersion $\sigma_\circ$, could be used to set constraints on the age dispersion among local ellipticals that would pos-
possibly be much tighter than those set by either optical colors or the fundamental plane relations. The approach would be the same that Bower, Lucey & Ellis (1992) have pioneered to set such constraints using the small dispersion about the average \((U-V) - \sigma_v\) relation of local cluster ellipticals, with one advantage. Indeed, \((U-V)\) evolves very slowly in old populations, i.e., by 0.02-0.03 mag/Gyr, while e.g. \((1550-V)\) should evolve 10, perhaps 20 times faster. In principle, rest frame \(UV - V\) colors could set \(\sim 20\) times tighter constraints to age dispersions. However, the time derivative of \((1550-V)\) as determined from synthetic populations is extremely model dependent, which therefore makes extremely attractive its direct, empirical determination. We speculate that extensive studies of the UV upturn for cluster vs. field ellipticals up to \(z \sim 0.5\) could greatly help tightening current constraints on the star formation history of early-type galaxies.

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