THE UV UPTURN IN ELLIPTICAL GALAXIES

H.C. FERGUSON
Space Telescope Science Institute
3700 San Martin Drive, Baltimore MD 21218, USA
(ferguson@stsci.edu)

Abstract. The hot stellar component in elliptical galaxies offers clues to both stellar evolution and galaxy evolution. Current observations suggest that extreme horizontal branch (EHB) stars dominate the far-UV emission from galaxies with the strongest "UV upturns," while post asymptotic giant branch (PAGB) stars are probably significant contributors for weaker galaxies. Spectra near the Lyman limit indicate that a rather narrow range of temperature (and hence EHB star mass) is required. However, other arguments suggest that *most* of the helium-burning stars in elliptical galaxies are in the red clump. The HB star mass distribution therefore appears to be strongly bimodal. Such bimodality is qualitatively reproduced by two radically different stellar population models, (those of Lee and Bressan *et al.*), both of which require that the galaxies be very old. However, the Galactic open cluster NGC 6791 also contains EHB stars and exhibits strong bimodality, indicating that old age may not necessarily be a requirement for the UV upturn phenomenon.

1. Introduction

In the question session at the end of Baade's first talk at the Vatican conference (Baade, 1958), Hoyle asked whether the stars of elliptical galaxies are similar in their composition to the stars in the halo, or to stars in the disk. The reply came from Morgan: *"From integrated spectra there is no doubt that the principal source of luminosity in the inner part of M31 and in the giant E0-E5 systems in the Virgo cloud is due to K and M giants with normal metal content. The contribution of the halo stars to the total luminosity is probably minor."*

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This evidence of composition differences between elliptical galaxies and the prototype "population II" stars marked a profound change from Baade's characterization of halo stars, globular clusters, and elliptical galaxies as one type of population. The comparison of elliptical galaxies with the Galactic populations remains relevant even today. Are the differences between E galaxy spectra and the spectra of globular clusters due only to chemical composition, or do differences in age also play a role?

In this conference, we have heard from Faber and others that line strengths (that of H_β in particular) in elliptical galaxy optical spectra suggest that many galaxies formed a significant fraction of their stars within the last $3-8$ Gyr. However, the strength of the H_β line, as with most other strong features in optical spectra, is primarily dependent on stellar effective temperature, rather than on gravity or metallicity. Strong H_β simply indicates that there is an excess "warm" population over that predicted by the models or seen in metal-rich globular clusters, not necessarily that it is young.

Another place where the simplest "old stellar population" models have consistently had trouble matching the observed spectra is in the far-UV. There are two reasons why a discussion of the UV upturn may be very relevant to the debate about E galaxy ages. First, as outlined below, the problem now seems to be intimately connected to understanding what governs horizontal branch (HB) morphology. The large observed variation in the 1550Å $-V$ colors of E galaxies illustrates that HB morphology varies markedly from galaxy to galaxy. This effect is not included in the Worthey (Worthey, 1992) models discussed by Faber at this meeting. Second, theoretical models of the UV upturn, which do predict changes in HB morphology (Lee, 1994; Bressan *et al.*, 1994), favor ages as old or older than Galactic globular clusters, in apparent conflict with the inferences from optical line strengths. In the discussion below we outline constraints on the stellar populations producing the UV upturn in elliptical galaxies, and argue that a physical understanding of the phenomenon is still lacking.

The "UV upturn" in elliptical galaxy spectra has been known since the early days of space astronomy. The strength of the upturn correlates most closely with metallicity, but also with luminosity, velocity dispersion, and other properties (Burstein *et al.*, 1988). There is strong evidence from imaging and spectroscopic experiments that young stars are not the source of the UV emission (Burstein *et al.*, 1988; Deharveng *et al.*, 1982; Bohkin *et al.*, 1985; Ferguson *et al.*, 1991). There are also strong arguments on both theoretical and observational grounds that PAGB stars are not the dominant source in galaxies with strong UV emission. The theoretical arguments stem from estimates of the PAGB star fuel consumption at high temperatures, which fall short of the required values by more than an or-

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der of magnitude for standard assumptions about the stellar death rate (Brocato *et al.*, 1990; Greggio and Renzini, 1990; Castellani *et al.*, 1991; Castellani *et al.*, 1992). The observational argument stems from the spectrum of the UV bright elliptical NGC 1399 obtained by the Hopkins Ultraviolet Telescope (HUT), which shows a characteristic temperature ~ 25000 K, as opposed to the > 50000 K temperature expected for PAGB stars (Ferguson *et al.*, 1991). This characteristic temperature is well-matched by models of stars evolving from the extreme horizontal branch through the "AGB-manqué" phase to the white-dwarf phase without ascending the asymptotic giant branch (Davidsen and Ferguson, 1992).

2. Theoretical Interpretation

Recent efforts to construct large grids of stellar evolution models with new opacities and a wide range of chemical composition offer the necessary framework to examine in detail the parameters that influence horizontal branch morphology, and hence could potentially account for the observed systematic trends in UV/optical flux ratios for elliptical galaxies. Of particular interest are three investigations (Lee, 1994; Bressan *et al.*, 1994; Dorman *et al.*, 1994) summarized in posters at this symposium. While there is general agreement that EHB stars are the dominant source of UV emission in UV bright E galaxies, there is a rather striking difference of opinion on why these EHB stars are present. In Lee's model, the EHB stars are part of an extremely old, metal poor population. Ages significantly older than Galactic globular clusters are required to push the mean temperature of stars blueward of the RR Lyrae gap high enough to match the spectroscopic constraints. Lee points out that if age is the parameter that controls the strength of the UV upturn, the steep observed gradients in 1550Å $-V$ colors would imply that most galaxies formed from the inside out, and the trend of decreasing $1550 - V$ color with luminosity would imply that more massive galaxies formed first. The observed correlation of 1550Å $-V$ color with metallicity is in this model an artifact of the general trend for more massive galaxies to have higher mean metallicity.

In contrast, Bressan *et al.*(Bressan *et al.*, 1994) attain rough agreement with the observed trend in $1550 - V$ *vs.* Mg_2 without requiring a very metal poor population or ages older than globular clusters. The source of the UV emission from the brightest galaxies in this model is EHB stars from a population with metallicity and helium abundance well above the solar values. The high helium abundance leads to a lower main-sequence turnoff mass at fixed age, and the high metallicity allows the stars, once they begin the core He-burning phase, to burn out the envelope much faster than stars of the same mass but lower metallicity. When the envelope mass decreases

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below a critical value the stars evolve to higher temperature and spend the bulk of their core He-burning phase at $T_{\text{eff}} \sim 25000\,\text{K}$. If the mass-loss parameter η (Reimers, 1975) is held fixed, the appearance of EHB stars at high metallicities is due primarily to the high helium abundance, requiring $\Delta Y/\Delta Z \gtrsim 2.5$. The color-magnitude diagram of the Galactic bulge provides some support for such a high value (Renzini, 1994).

Dorman *et al.*(Dorman *et al.*, 1994; Dorman *et al.*, 1993) remain somewhat agnostic on what actually leads to the presence of EHB stars, but instead try to derive relatively model-independent constraints on the fractions of EHB stars needed to reproduced E galaxy UV and optical colors. They conclude that the EHB fraction ($< 5\%$) required for most galaxies is comparable to the fraction of hot subdwarfs in the Galactic disk, but galaxies with strong upturns require fractions as high as $\sim 20\%$. They argue that high metallicity is more plausible than high helium abundance as the parameter driving the enhanced EHB star fraction.

3. Further Observational Constraints

The early analysis of the HUT spectrum of NGC 1399 (Ferguson *et al.*, 1991) was limited by the availability of model atmospheres at the appropriate temperatures and resolutions, and evolutionary tracks covering a wide range of HB star masses and compositions. We are taking steps to remedy these shortcomings, and report here on a couple of preliminary conclusions. The HB evolutionary tracks are from Dorman *et al.*(Dorman *et al.*, 1993).

We first address what can be learned from the profiles of the Lyman series lines in the NGC 1399 spectrum. To model the spectrum at the full resolution, stellar model atmospheres have been constructed with Hubeny's TLUSTY and SYNSPEC codes (Hubeny, 1988), over a range of temperatures and gravities. These models do not at the moment include the same sources of continuum opacity as the Kurucz models, but the conclusions drawn below should be relatively insensitive to that deficiency. Fig. 1 shows the HUT raw spectrum at full resolution. The Lyman β, γ and δ lines are clearly seen in absorption, separated from geocoronal emission by the redshift of the galaxy. Composite spectra have been constructed from the individual evolutionary tracks to represent HB stars of a single mass. The synthetic spectra are broadened by the galaxy velocity dispersion and instrumental resolution, and folded through the HUT sensitivity curve for comparison to the data. Models with low envelope masses provide very good fits to the Lymanβ and γ profiles (not so good for Ly δ), providing confirmation that at least the temperatures and gravities of these stars are about right, and that the contribution from a much hotter component (e.g. PAGB stars) must be very small.

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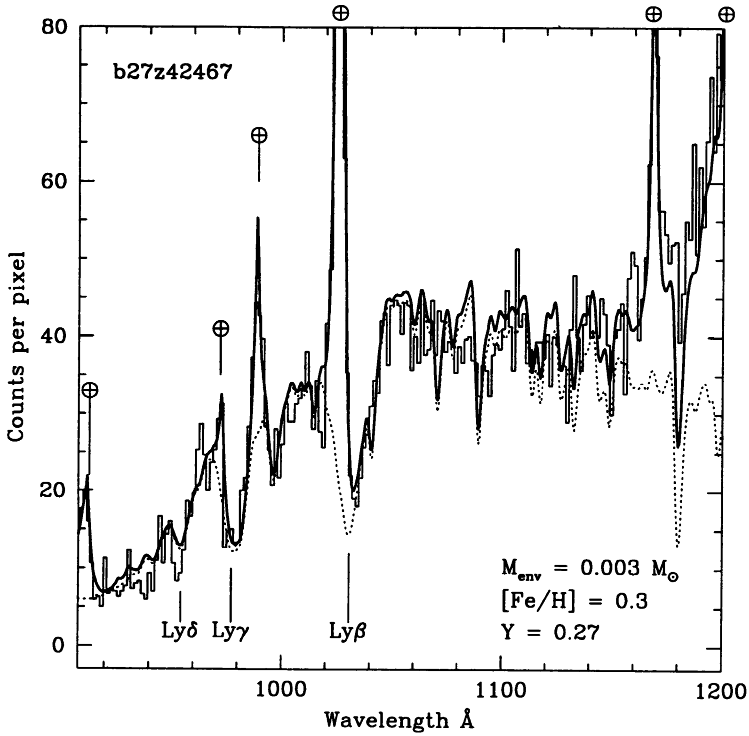

Figure 1. Model fit to the Lyman-series region of the HUT spectrum of NGC 1399. The histogram shows the data in counts per 0.51Å pixel. The solid line is the best fit model, which represents a population of EHB/AGB-manqué stars with [Fe/H] = 0.3, solar He abundance, and an envelope mass of $0.003 M_\odot$. The emission lines are all airglow. The steep rise at the red end of the spectrum is due to scattered geocoronal Lyman α. The model also includes absorption due to Galactic HI as a free parameter (best fit $\log N_{\rm H} = 19$). Interstellar absorption at the redshift of NGC 1399 is not included. The dotted line shows the model spectrum without airglow or interstellar absorption. The best-fit $\chi^2 = 835$ with 510 degrees of freedom ($\chi^2/\nu = 1.6$).

The temperature and gravity sensitivity of the models are illustrated in Fig. 2, where we plot synthetic spectra of individual stars for various values of $T_{\rm eff}$ and $\log g$. The profiles of the Lyman β and γ lines are best matched with gravities that are roughly appropriate for EHB stars, although temperatures a bit hotter than the typical upper limit of the zero-age HB (ZAHB) evolutionary tracks seem to be preferred. None of the individual star models provides as good a fit to the data as the composite HB star model. The models are not at this point capable of distinguishing between metal-rich and metal-poor EHB stars. Note that the C III λ1175 line is clearly present, while the C II λ1037 line is not. Ultimately, models of these line strengths, together with those of He and N, may offer some constraint on

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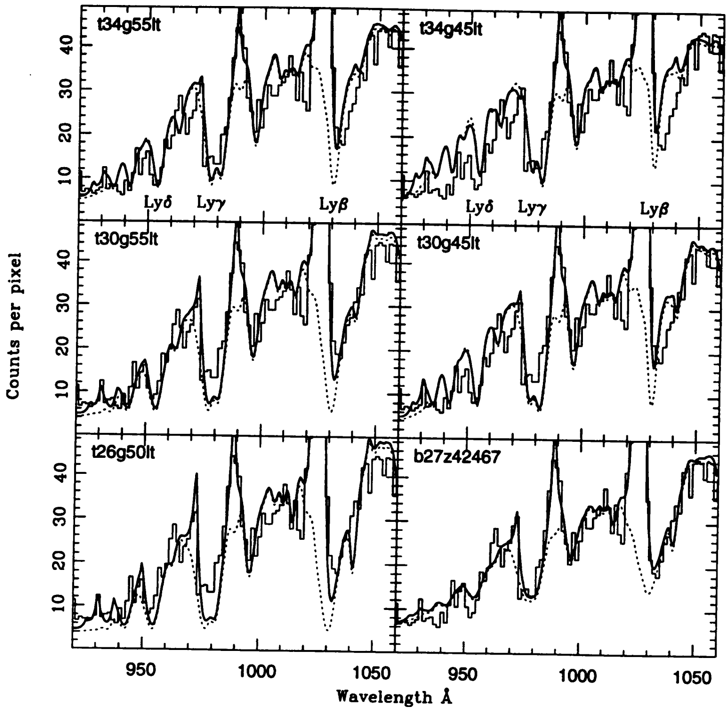

Figure 2. The first five panels show synthetic spectra of individual stars compared to the HUT NGC 1399 spectrum. The temperature and gravity are coded in the upper left corner (e.g. t34g55lt is an LTE model for $T_{\rm eff} = 34000\,{\rm K}$, $\log g = 5.5$). The final panel shows the same model as in Fig. 1. The breadth of the Lyman β and γ lines favors gravities $5 < \log < 6$ in this temperature range. Perhaps fortuitously, the composite EHB model provides a much better fit to the data (the best fit single star, shown in the first panel, has $\chi^2 = 1078$, compared to 835 for the composite EHB model).

the contribution to the total flux from stars that have completely stripped their envelopes (Greggio and Renzini, 1990). Such tests will be particularly interesting with the higher signal-to-noise ratio expected from further HUT observations during the Astro-2 mission.

The second issue of some importance for understanding the origin of the UV upturn is the distribution of stars along the horizontal branch, which is in essence the distribution of envelope masses. From the existence of the planetary nebulae, we know that at least some stars are able to ascend the AGB, and hence must endure an HB phase with large envelope masses. However, the stellar death rate estimated from the planetary nebula luminosity function is well below that estimated from the bolometric luminosity. Hence many of the stars do not channel into the PN phase. If the stars were

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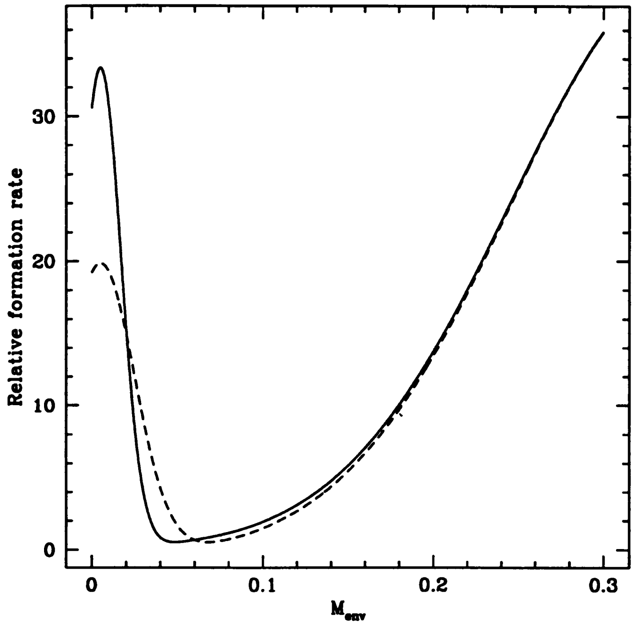

Figure 3. The HB-star formation rate as a function of envelope mass inferred from the HUT spectrum. The solid curve is a bimodal distribution with mean envelope masses $M_{\rm EHB} = 0.004$ and $M_{\rm RHB} = 0.346$, and Gaussian widths about those means of $\sigma_{\rm EHB} = 0.012$, and $\sigma_{\rm RHB} = 0.10$. (The models are constructed by computing weights for the different Dorman models by integrating under the curve shown. Stars with negative envelope mass are included in the lowest $M_{\rm env}$ bin.) The dotted curve has $\sigma_{\rm EHB} = 0.020$ and is excluded at a high level of confidence.

evenly spread out from the red clump to the EHB, the spectrum observed by HUT would be relatively flat. Since it is not flat, but rises toward the far-UV, there must be some bimodality in the temperature distribution of the stars. Evolution off the ZAHB leads to a natural bifurcation, as blue stars evolve more to the blue, and red stars more to the red (Dorman *et al.*, 1993). Is that enough, or must the rate of formation of the HB stars vary as a function of envelope mass? To investigate this, we once again construct synthetic spectra of single-mass HB star populations, this time with the Kurucz (Kurucz, 1992) models over the full HUT wavelength range. As with the higher resolution models, the best fits are for low envelope mass. As a simple experiment, we assume that the mass distribution is a superposition of two Gaussians, with means $M_{\rm EHB}$ and $M_{\rm RHB}$ and widths $\sigma_{\rm EHB}$ and $\sigma_{\rm RHB}$. The solid line in Fig. 3 shows an example of a distribution of EHB star formation rates that leads to an acceptable fit to the HUT spectrum. The dotted line shows a distribution that does not lead to an

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acceptable fit (the spectrum is much too flat). The conclusion is that the EHB stars must form in a clump at very low envelope mass.

While both the Lee (Lee, 1994) and Bressan *et al.*(Bressan *et al.*, 1994) models produce bimodal HB distributions, it is not obvious that they can produce anything as narrow on the blue end as $\sigma_{EHB} = 0.01M_{\odot}$. In the Lee model, the bimodality is mostly sensitive to age, and the observations would seem to require ages many Gyr older than globular clusters. In the Bressan *et al.*model the HB morphology is very sensitive to both age and composition. The resulting spectrum may therefore be very sensitive to technical aspects of the modeling; for example, the details of interpolating between $Z = 0.05$ and $Z = 0.1$ HB evolutionary tracks (which show quite different behavior), or any assumed spread in mass loss at fixed age and composition (an effect not included in their models). We suspect that producing an EHB clump as narrow as $\sigma_{EHB} = 0.01M_{\odot}$ is problematic for *any* model where the HB morphology is governed by smooth underlying distributions of age and chemical composition.

Nevertheless, Nature appears to have found a way to produce such distributions in populations in the disk of our own galaxy (Dorman *et al.*, 1994). The field sdB stars represent $\sim 2\,\%$ of the HB population of the old (thin) disk (Saffer, 1991). In their atmospheric parameters, these stars follow the evolutionary tracks for EHB stars with $M_{\rm env} < 0.02M_{\odot}$ (Liebert *et al.*, 1994). However there is a rather pronounced minimum temperature of 25000 K in the observed distribution, which does not appear to be due to selection effects (Newell, 1973; Liebert *et al.*, 1994). Such a minimum is similar to what is needed to account for the shape of elliptical galaxy UV spectra, although the proportion of the population going through the EHB phase must be much higher in a UV bright galaxy such as NGC 1399.

The most striking example of HB bimodality is seen in the old disk open cluster NGC 6791. Liebert *et al.*(Liebert *et al.*, 1994) have spectroscopically identified four EHB stars, with envelope masses $< 0.01M_{\odot}$. Based on timescales from the evolutionary tracks (Dorman *et al.*, 1993), these EHB stars represent about 15 % of the HB population. From experiments with bimodal HB distributions similar to those described above for E galaxy spectra, Liebert *et al.*conclude that dispersions in envelope mass $\sigma_{\rm EHB} \sim 0.01M_{\odot}$ are required to reproduce the observed color-magnitude diagram.

The disk EHB population is unlikely to be older than 10 Gyr or exceed solar metallicity or helium abundance. The age of NGC 6791 inferred from the color-magnitude diagram is ~ 9 Gyr (Garnavich *et al.*, 1994), and its metallicity is [Fe/H] ~ 0.2 (Friel and Janes, 1993). Thus neither old age nor extremes of composition appear to be required to reproduce EHB stars with roughly the temperature distribution needed to match elliptical galaxy

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spectra. As this phenomenon is seen in an individual cluster, it also appears that composition and age spreads are not required to produce bimodal HB morphologies. However, the HB morphologies in these local populations and that inferred from the NGC 1399 spectrum seem too close to ignore; they suggest that the explanation for the UV upturn lies in some physics not included in current models of stellar evolution.

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KING: The spectrum on which Morgan saw the strong lines in M31 was an old one that had been taken by Mayall. Morgan had spent a summer at Lick Observatory working wiht Mayall, and this visit resulted in the discovery of strong lines in M31 and ellipticals, and a range of line strengths in globular clusters.

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BELL: Were the evolutionary tracks calculated using Los Alamos opacities, and, if so, would using OPAL opacities make any difference?
DORMAN: Probably very little, since all metal–rich compositions for [Fe/H] > -0.47 have horizontal branches that behave similarly (most masses are red, some range blue, with very small mass range in between). The details of which tracks have a given $T_{eff}(M_{env})$ relation will change, perhaps, but not the qualitative behavior.
WHITE: Can you test the picture you are proposing by looking at higher redshift and seeing if you detect the expected trend in UV upturn as the ellipticals get younger?
FERGUSON: This is obviously an important test of the various ideas being considered. There are several groups trying to do what you suggest, but it is pushing the HST sensitivity.
LEE: I would like to stress that the crux of this business (modelling the UV upturn) is whether you can reproduce the bimodal effective–temperature distributions. As you pointed out, my HB models (Lee, 1994) can reproduce this, only if the metallicity distribution is large, as anyone believes. I consider this the most important feature of my models, which can reproduce the bimodel T_{eff} distribution without any "ad hoc" assumptions needed in alternative models.
FERGUSON: It was my impression from your Ap. J. letter that the sort of bimodality we infer from the HUT spectrum is more extreme than you would expect from your model, or would at least push things to very old ages.
WYSE: Could you comment on constraints from radial gradients?
FERGUSON: For the most part, the UV surface brightness profiles are much steeper than the optical profiles. Galaxies are bluest in 1550–V color in the center. The exception is M32, which is redder in the center. The gradients are one of the strongest pieces of evidence that the UV upturn is somehow related to metallicity. However, I think more work needs to be done to determine just how well the 1550–V tracks the metallicity gradients within individual galaxies.
LIEBERT: I cannot resist commenting that NGC 6791 violates the three alleged truisms favoring BHB/EHB stars in globular clusters – it is NOT extremely old, NOT metal–poor (rather the most metal–rich cluster known in the Galactic disk), and NOT a high stellar density. I suggest that globular clusters are not the right comparison, because the HB of NGC 6791 is so bimodal it suggests a different origin for the hot and cold stars. I wonder if the interesting (case B) binary scenario can yet be made to work.

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