UV Emission from Elliptical Galaxies Near and Far

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Abstract. The far-ultraviolet is the most rapidly evolving portion of the spectrum in both very young galaxies and very old galaxies. The “UV upturn” in the spectra of elliptical galaxies shortward of 2000 Å offers a promising probe of the ages and chemical evolution of very old galaxies. In early-type non-active galaxies with the bluest $1550 - V$ colors, the bulk of the emission arises from Extreme Horizontal Branch (EHB) stars, along their evolution from the zero-age HB to the white-dwarf cooling curve. The strength of the UV-upturn is governed by the fraction of stars that evolve through the EHB phase, which is in turn governed by age, metallicity, helium abundance, and other parameters such as stellar rotation and binarity that might influence the amount of mass loss on the RGB. Spectral constraints on the nature of the hot stellar population from Astro-2 are reviewed, and new imaging results from the HST Faint Object Camera are presented. Attempts to measure evolution through observations of high-redshift elliptical galaxies in the rest-frame UV are reviewed.

BACKGROUND

Giant elliptical galaxies show a large variation in the ratios of their far-UV to optical fluxes. Shortward of 2000Å, most ellipticals have spectra that rise in $f_{\lambda}$ toward shorter wavelengths. This hot component has been known since the early days of space astronomy [1]. Observations and theory now seem to be converging on a consensus that the dominant component in UV bright galaxies is extreme horizontal branch (EHB) stars and their evolutionary progeny [2–8]. This conclusion stems from the rather cool temperature (25000 K) derived for the dominant component in NGC1399 [9], and from computations that indicate that EHB stars can provide enough far-UV photons over their lifetimes to produce the elliptical galaxy fluxes, while other candidates such as PAGB stars cannot.

While it seems clear that EHB stars provide the far-UV flux, it is less clear how they got there. The general trend observed for globular clusters is...
that the horizontal branch (HB) becomes redder with increasing metallicity. Elliptical galaxies are even more metal rich than Galactic globular clusters; they must somehow be able to buck the trend. The HB morphology depends on age, metallicity, helium abundance, and the amount of mass loss on the red giant branch. The helium-burning core in HB stars has a mass ($0.5 \ M_\odot$) that is nearly independent of these parameters. The position of stars along the HB thus depends on the envelope mass, which in turn depends on the main-sequence mass and the amount of mass lost during the RGB phase. EHB stars (those with $T_{\text{eff}} > 20000$ K) have envelope masses less than $0.05 M_\odot$. Hence they must arise from stars that have lost nearly all the mass it was possible for them to lose and still ignite helium in their cores.

There are several plausible ways to produce a minority population of EHB stars in elliptical galaxies.

First, the giant elliptical galaxies may in general be older than the galactic globular clusters. This argument is a natural extension of the interpretation of the second parameter effect in globular clusters as being due to variations in age [10,11]. The EHB stars in this model represent the extreme metal-poor tail of the metallicity distribution, and are 2-4 Gyr older than the most-metal poor globular clusters. They show up in giant elliptical galaxies, which are on average metal rich, because these galaxies formed first, and hence have the oldest stars.

Second, elliptical galaxies may have high helium abundance $Y$ [2,5,12]. At fixed age and metallicity, the main-sequence lifetime decreases with increasing $Y$. Observations of nearby star-forming galaxies and the galactic bulge hint at a rather steep relation ($\Delta Y/\Delta Z > 2$) between helium abundance and metallicity [13,14]. If this is the case, then old metal-rich populations may have EHB stars, even with standard RGB mass-loss rates. The required ages (> 7 Gyr) are not as extreme as in the Lee model. In these models, the EHB stars arise from the extreme high-metallicity tail of the abundance distribution.

Third, some other process may act to increase mass loss in a small fraction of the population. For example, EHB stars could arise from stars in close binary systems that have shed their envelopes during interactions with their companions, or they could arise only from stars with high rotation rates. Such mechanisms could produce EHB populations from anywhere in the abundance distribution, but might be enhanced in giant ellipticals through some secondary effect (for example binary fraction might somehow depend on galaxy metallicity or velocity dispersion). In this case, the EHB stars may come closer to reflecting the mean metallicity of the stellar population.

Whatever the mechanism for producing them, the fraction of EHB stars is likely to be sensitive to age, because the main-sequence turnoff mass is one of the parameters that influences the mass on the horizontal branch. Indeed, it is likely that the fraction of EHB stars is the most sensitive indicator of age for stellar populations older than ~ 5 Gyr. For solar metallicity and ages 5-18 Gyr, the turnoff mass varies as $-0.63 \log(\text{age})$, according to the Padova
isochrones. A difference of 0.05 \(M\odot\) is enough to move a star from the UV-weak to the UV-strong portion of the horizontal branch. In a population with fixed age and chemical abundance and where no other parameters influence horizontal-branch mass, a change in age of only 10% could introduce changes in the UV/optical flux ratio of more than an order of magnitude.

The problem in using the UV upturn in elliptical galaxies as an age indicator is that it lacks a calibration, either empirical or theoretical. Clearly we need a better understanding of the EHB star population and the mechanisms that produce it.

What follows is a summary of attempts to constrain the metallicity and helium abundance of the UV-emitting population from Hopkins Ultraviolet Telescope (HUT) spectra, a preliminary discussion of the properties of far-UV point sources seen in new images of the centers of M31 and M32, and a summary of attempts to detect evolution in the far UV emission from ellipticals as a function of redshift.

**ASTRO-2 SPECTROSCOPY**

During the Astro-2 shuttle mission in March 1995, HUT [15,16] observed six elliptical galaxies, obtaining spectra at a resolution of 2-4\(\AA\) over the wavelengths from 912-1840\(\AA\). The 10\(\arcsec\)\times 56\(\arcsec\) slit covered the central regions of each galaxy. The results of the observations and modeling are described in detail by Brown and collaborators [6,7].

To model the observations, we have constructed synthetic FUV spectra for old stellar populations by integrating individual synthetic stellar spectra over stellar evolutionary tracks. The Dorman et al. [17] evolutionary models were used for EHB stars and their progeny (AGB-Manqé and PEAGB stars). A new set of model atmospheres of hot stars were constructed for this purpose [18]. Composite spectra were constructed for each of over one hundred evolutionary tracks.

Diffusion processes in the outer layers of hot, high-gravity stars create inconsistencies between the abundances that determine the evolution of the stars and the abundances in outer layers of the stellar atmospheres [19–21]. For this reason, we have constructed synthetic spectra with three different atmospheric metallicities (\(Z_{\text{atm}} = Z_\odot, Z_{\text{atm}} = 0.1Z_\odot, \) and \(Z_{\text{atm}} = 0.01Z_\odot\)) for all of the different evolutionary paths, regardless of the underlying abundance.

The galaxies have each been fit with single-mass populations of EHB stars, and with composite populations of EHB stars + PAGB stars. The composite population models are more consistent with the data. The best fits have small fraction of the light coming from PAGB stars (less than 20% at 1400\(\AA\)), but nevertheless a large fraction (more than 92%) of the stars evolve through the PAGB phase. Figure 1. shows the results for NGC 4649 for models of different metallicity and helium abundance. The evolutionary tracks with high helium
**FIGURE 1.** The best-fit PAGB+EHB star evolutionary model from each of the Dorman et al. (1993) abundance subsets. The HUT spectrum of NGC 4649 (M60) is shown as a solid histogram; the models are shown as dashed lines. The chemical abundances and envelope mass $M_{\text{env}}$ are shown for each track; the atmospheric abundance is $0.1Z_\odot$. The parameter $\Delta F$ is the fractional flux deficit in the models relative to the data over the wavelength interval 912-970 Å. Models with subsolar evolutionary abundances (shown in the panels on the left) significantly underpredict the observed flux shortward of 970 Å.
abundance and high metallicity (shown in the right-hand panels) produce the best fits. The low-metallicity alternatives do not produce enough flux near the Lyman limit.

The best-fit models have stellar-atmosphere abundances \( Z_{\text{atm}} = 0.1Z_\odot \). The preference for this abundance over solar or 0.01 solar can be seen quite clearly in Fig. 2. However, because roughly half the flux comes from stars in the gravity+temperature regime where a complicated balance between radiative levitation, gravitational settling, and stellar winds determines the line strengths, we do not believe the result rules out either the metal-rich or the metal poor scenario. Among the six galaxies observed on Astro-2, there is a tendency for galaxies with stronger UV upturns to have stronger lines, as expected in the high-metallicity scenario [7].

**FOC IMAGING**

To provide another view of the far-UV emitting population, the nearby galaxies M31 and M32 were observed with the HST Faint Object Camera. The images were taken through the F175W and F275W filters (the numbers correspond to the filter central wavelengths in nm). Figures 3 and 4 show color images constructed from the two FOC bands and a WFPC-2 F555W band image. Preliminary color magnitude diagrams are presented by Brown et al. (this volume). There are several inconsistencies in the photometry that must be cleared up before trusting detailed comparisons to the theoretical evolutionary tracks. Nevertheless, broadly speaking the stars populate the portion of the CMD expected from the spectral analysis.

Above the 6σ detection limit 1349 sources are found in M31 and only 183 in M32. These resolved sources account for only a small portion of the far-UV flux in each galaxy. In M31 the resolved sources produce 39% of the flux at 1700 Å, while in M32 they account for only 8%. Both numbers are a bit uncertain due to the photometric errors, and because some scaling had to be applied to convert from the IUE aperture to the FOC aperture (assuming the UV surface brightness profile traces the optical profile, which may not be a very good assumption). Note, however, that this calculation is insensitive to red-leak because the sources themselves are UV bright and the estimate for the total UV flux comes from IUE which is not affected by redleak (or red scattered light).

The fraction of the UV emission that is resolved in M31 is in keeping with expectations, because much of the far-UV flux arises from stars near the zero-age HB, which is well below the detection limit of the images. For M32, the small fraction of the flux that is resolved is a bit of a surprise, although it was hinted at by earlier FOC observations [22,23]. The implication is that most of the far-UV emission from M32 is *not* due to low-mass PAGB stars. In a population of pure PAGB stars less massive than 0.7\( M_\odot \) at least 15%
FIGURE 2. The HUT data for NGC 4649 (histogram) are plotted with the best fit EHB+PAGB model (curve). The best-fit model has supersolar evolutionary abundances ($Z = 0.04$, $Y = 0.27$), but we have synthesized the spectrum with model atmospheres of three different abundances. The center panel, with $Z_{\text{atm}} = 0.1 \, Z_{\odot}$ provides the best match. Small differences in the data shown in each panel are due to variations in the airglow subtraction, since the airglow line fluxes were free parameters in the fits.
of the far-UV flux comes from stars with temperatures $10^4 < T < 10^5$ K and luminosities $\log L/L_\odot > 3$. Such stars would be easily detected in the FOC images. For typical PN central stars of mass $0.6M_\odot$ the contribution from resolved sources should be more than 50%. Most of the far-UV emission in M32 must come from another source. One possibility is that the diffuse light comes from normal blue HB stars in the metal-poor tail of the metallicity distribution. Such emission should be present in all elliptical galaxies, but is usually overwhelmed by the UV-upturn component.

**EVOLUTION WITH REDSHIFT**

An obvious test of our understanding of the UV upturn phenomenon is to try to detect the very strong evolution predicted by theory. In either the metal-rich or the metal-poor scenario, the UV upturn should disappear at lookback times of only 2-5 Gyr. By $z > 0.3$, there should be no elliptical galaxies with optical spectra consistent with passive evolution and strong UV upturns.

Numerous attempts have been made to confirm this prediction using HST. To date all such attempts have been foiled by either poorer than predicted sensitivities or poor understanding of scattered light. No galaxies have been detected (save for Ly\(\alpha\) emission from a few radio galaxies), but the upper limits do not constrain the theory.

The Hubble Deep field provides a new data set to attempt to detect this evolution. Redshifts have been measured now for over 100 galaxies in the image, of which about eight appear morphologically to be ellipticals. Figure 5 shows the spectral energy distributions derived from the HDF images and the Hawaii [24] IR images for galaxies with $0.3 < z < 0.7$. Of the four galaxies, two are detected at rest-frame wavelengths below 2000 Å, and two have only upper limits. For the two detected, it will be important to get data at shorter wavelengths (possible with STIS), and get high S/N spectra in the optical to assess whether the spectrum is consistent with pure passive evolution.

It will be difficult to get a definitive answer from a few random field galaxies, since it is possible for a short burst of star formation to produce a UV upturn without significantly affecting the optical spectrum (although one might imagine detecting [OII] and/or H\(\alpha\) emission in this case). A better measure of evolution will come from observations of several elliptical galaxies in each of several clusters at different redshifts. We can hope to see such observations emerging from STIS in the next few years.

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**FIGURE 3.** Color image of M31 constructed from FOC F175W and F275W images and a WFPC-2 PC image taken with the F555W filter. The field of view is $14 \times 14$ arcsec. More than 1000 UV-bright sources are detected.

**FIGURE 4.** FOC + WFPC-2 Image of the center of M32. The field of view is the same as for M31.
FIGURE 5. Evolution of the UV upturn. Four elliptical galaxies from the Hubble Deep field with measured redshifts are shown, together with composite optical and UV spectra of NGC 1399 and M31 (the optical and NUV portion of the M31 spectrum is courtesy of Daniela Calzetti).
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