Far-UV Line Strengths in Elliptical Galaxies

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**Abstract.** Much of the far-UV emission from elliptical galaxies is thought to arise from extreme horizontal branch stars and related objects. Only about 10% of the stellar population needs to evolve through this phase even in galaxies with the strongest UV upturn. However it is not yet clear if this population represents the extreme low-metallicity or high-metallicity tail of the distribution, or rather arises from the overall population through some metallicity-insensitive mechanism that causes increased mass loss in a small fraction of RGB stars. We investigate the utility of far-UV line strengths for deciding between these possibilities. Complications include the fact that the line strengths reflect both the temperature distribution and the metallicity distribution of the stars, that there may be abundance anomalies introduced on the RGB, and that metals are likely to be redistributed by gravitational settling and radiative diffusion in the atmospheres of hot high-gravity stars. Line-strength measurements from Astro-2 HUT spectra are considered in this context.

1. Introduction

Giant elliptical galaxies show a large variation in the ratios of their far-UV to optical fluxes. Shortward of 2000 Å, 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 ([Code and Welch 1979](#)), but it is only within the last two years that observations and theory 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 ([Ferguson and Davidsen 1993](#), [Dorman, O’Connell, and Rood 1995](#), [Bressan, Chiosi, and Fagotto 1994](#), [Brown, Ferguson, and Davidsen 1994](#)). This conclusion stems from the rather cool temperature (25000 K) derived for the dominant component in NGC1399 ([Ferguson et al. 1991](#)), 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 ([Greggio and Renzini 1990](#), [Dorman, O’Connell, and Rood 1995](#)).
While it seems clear that EHB stars provide the far-UV flux, it is not at all 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 $T_{\text{eff}} > 20000 \, \text{K}$) 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 (Lee 1994; Park and Lee 1995). 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 $Y$ (Greggio and Renzini 1990; Bressan, Chiosi, and Fagotto 1994; Yi et al. 1995). 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 (Pagel 1989; Renzini 1994). 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.

To distinguish between these possibilities, it is important to try to get some direct measure of the metallicities of the far-UV emitting population, as suggested for example by Park and Lee (1995) and Yi et al. (1995). It is now possible to attempt this with new observations from the Hopkins Ultraviolet Telescope (HUT), obtained March 1995 during the Astro-2 mission. In the rest of this contribution we summarize our preliminary attempts to do this, and outline some arguments why such efforts may in the end yield ambiguous results.
2. Observations

Elliptical galaxies were among the prime targets for the Hopkins Ultraviolet Telescope (HUT) on both the Astro-1 and Astro-2 missions. The HUT spectra cover the wavelength range from 1820 Å to the Lyman limit at a resolution of about 3 Å. Brown, Ferguson, and Davidsen (1995) present spectra for six galaxies observed on the Astro-2 mission. Some absorption line features are clearly visible in the spectra of individual galaxies, including strong Lyβ and Lyγ, and clearly visible CIII] 1175. To improve the S/N to the point where weaker features are measurable, we have summed together the two UV-bright galaxies: NGC1399, from Astro-1, and NGC4649 (M60), from Astro-2. For comparison, we have summed together the UV-weaker galaxies NGC3379, NGC4472 (M49), and NGC3115. The Astro-1 M31 spectrum, although of reasonably high S/N, is not included in this comparison because (1) it is contaminated by interstellar lines due to its low galactic latitude and low redshift, and (2) its far-UV spectral energy distribution is significantly different from that of other galaxies with similar 1550-V colors.

The Astro-2 observing program also included several Galactic sdB stars from the survey by Saffer et al. (1994). These stars are local examples of the stars that might be producing the far-UV emission in elliptical galaxies. (Their existence in the disk of our galaxy is at least as puzzling as the existence of EHB stars in elliptical galaxies.) The sdB star observations were included to provide a sensitive test of model atmospheres in the temperature and gravity range relevant to elliptical galaxies. The sdB star PG1710+490, with $T_{\text{eff}} = 29900$ K by itself provides a fairly direct comparison to a star at roughly solar metallicity. Line strengths are sensitive to both metallicity and temperature. To try to separate the two effects, we have used the Hubeny (1988) TLUSTY and SYN-SPEC codes to construct line-blanketed spectra for a grid of parameters ($T_{\text{eff}}$, log(g), and [Fe/H]) which cover the range relevant to the Dorman EHB models. For $T_{\text{eff}} \leq 20,000$ K, we used the Kurucz (1993) atmospheric structure as SYN-SPEC input. For the ranges $20,000$ K $< T_{\text{eff}} < 45,000$ K and $T_{\text{eff}} \geq 45,000$ K, we generated LTE and NLTE atmospheres of pure H + He, and used them as SYN-SPEC input. SYN-SPEC then generates the emergent spectrum using line opacities from those elements with atomic number $Z \leq 28$. The grid spacing in gravity is 0.25 and 0.5, respectively, for the Hubeny and Kurucz atmospheres, while the irregular spacing in $T_{\text{eff}}$ varies from 2000 K to 10000 K, as one moves from cooler to hotter grid temperatures. Although the models are clearly only an approximation to real stellar atmospheres, the purpose here is to identify useful wavelength ranges for testing for metal abundance, and to see qualitatively how the line strengths vary with abundance. The density of lines in the spectra shortward of 1200 Å is so great that each HUT resolution element contains hundreds of unresolved lines. Thus, measurements of the line strengths do not provide an unambiguous measure of which elements are varying, just an indication of whether the abundances are much above or below the solar value.

In Figure 1 the summed HUT spectra are compared to PG1710+490, and to two models constructed using the Dorman et al. (1993) EHB evolutionary tracks. While the evolutionary track is appropriate for abundances $Y_{ZAMS} = 0.34$, $Z_{ZAMS} = 0.04$, for the synthetic spectra shown in Fig. 1, we have used stellar atmospheres at solar abundance and 0.01$Z_{\odot}$ to illustrate the effect of
Figure 1. Spectra from Lyman α to the Lyman limit. The top and bottom panels show sums of elliptical galaxy spectra. The ones in the top panel are the strongest UV emitters; the ones in the bottom panel are somewhat weaker. The middle three panels show comparison spectra (described in the text). The shaded regions are used as the line regions for the spectral index measured in Table 1. The continuum regions are shown as horizontal lines.
changing the atmospheric opacities while holding the underlying temperature and luminosity distribution fixed. The galaxy spectra show some features in common with the sdB star, and are missing others (most notably the strong nitrogen feature at 990 Å). The absorption features appear on average slightly weaker than the sdB star or the solar-metallicity EHB star model, but the galaxy spectra have more structure than expected from a population with \( [\text{Fe}/\text{H}] = -2 \). The Lyman series lines are not as deep in the elliptical galaxies as in the sdB star or the models. A 10-20% flux contribution from PAGB stars, which have weak Lyman series and metal lines, would be sufficient to bring the Lyman series lines into agreement and to dilute the metal-line features. Thus even if the EHB stars themselves are a metal-rich population, we might expect to see somewhat weaker lines than in individual Galactic subdwarfs. However, our synthetic spectra for the sdB star have Lyman series lines that are stronger than observed, so we are not yet confident that the Lyman series line strengths can be used to set quantitative limits on the PAGB contribution.

| Source       | 1550-V (mag) | CIV (mag) | E.W. Å  | SiIV E.W. Å |
|--------------|-------------|-----------|--------|-------------|
| N4649        | 2.24        | 0.13 ± 0.07 | 3.0 ± 3.3 | 2.2 ± 4.0   |
| N1399        | 2.05        | 0.04 ± 0.09 | 4.8 ± 6.3 | 2.5 ± 6.3   |
| N4649+N1399  | 2.14        | 0.11 ± 0.06 | 3.4 ± 3.0 | 2.2 ± 3.4   |
| N3379+N3315+N4472 | 3.64 | 0.09 ± 0.11 | 1.6 ± 3.8 | 2.2 ± 5.7   |
| PG1710+490  | —           | 0.05 ± 0.00 | 2.5 ± 0.0 | 1.9 ± 0.0   |
| EHB model \( Z_\odot \) | —         | 0.14 ± 0.00 | 1.9 ± 0.0 | −0.8 ± 0.0  |
| EHB model 0.01\( Z_\odot \) | —         | 0.01 ± 0.00 | 0.5 ± 0.0 | −2.5 ± 0.0  |

1550-V colors are taken from Burstein et al. 1988

\( I_1 \) is expressed as a magnitude. Bandpasses are shown in Fig. 1

Si IV line: \( \lambda 1385 − 1440 \), continuum \( \lambda 1360 − 1380, 1445 − 1500 \)

C IV line: \( \lambda 1540 − 1565 \), continuum \( \lambda 1480 − 1540, 1570 − 1620 \)

The comparison of line strengths is quantified in Table 1. At the low S/N of the HUT spectra, it is difficult to measure individual lines. To improve the statistics, we have concocted a composite metal line index based on the features seen in the sdB star PG1710+490. The line and continuum regions are shown in Fig. 1. The absorption features are due primarily to Si, C, and N. Following standard practice, we express the result as a magnitude (\( I = -2.5 \log f_x(\text{line})/f_x(\text{continuum}) \)). For comparison to model predictions (Park and Lee 1993; Yi et al. 1993), we also show Si IV and C IV equivalent widths. For this purpose we have also used an HST FOS spectrum of NGC1399 to improve the signal to noise ratio. The results favor roughly solar metallicity, but metallicities as low as \( [\text{Fe}/\text{H}] = -2 \) or as high as \( [\text{Fe}/\text{H}] = 1 \) are still allowable within the 3\( \sigma \) uncertainties.

There is an extensive literature on abundances in the atmospheres of galactic sdB stars (e.g. Michaud et al. 1985; Lamontagne, Wesemael, and Fontaine 1987; Bergeron et al. 1988). These stars are observed to be strongly depleted in
helium. For temperatures lower than $T_{\text{eff}} = 35000$ K, abundances of C, N, and Si are close to solar. At higher temperatures, C and N are slightly depleted and Si is depleted by a factor of $10^4$. The line strengths in these non-convective, high-gravity atmospheres are governed primarily by a competition between downward diffusion and radiative levitation, rather than by the intrinsic elemental abundances. In the absence of radiative forces, metals would quickly diffuse out of the surface layers of EHB star atmospheres and the spectra would be extremely weak-lined. However, at EHB temperatures radiation pressure is sufficient to balance the gravitational force. Metals settle to an equilibrium depth where the lines are just saturated. If they settle further, the lines become unsaturated and the radiation pressure increases, while if they move higher in the atmosphere the lines become strongly saturated and the radiation pressure is no longer efficient. This equilibrium state can be upset by winds, possibly explaining the Si deficiency at high temperatures (Bergeron et al. 1988). These considerations suggest that interpretation of the far-UV line-strength measurements may not be as straightforward as originally suggested, and may require detailed understanding of the atmospheres of hot subdwarfs.

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