Ultraviolet Light from Old Stellar Populations

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Abstract:

We consider the general theoretical problem of ultraviolet light from old stellar populations $(t \gtrsim 2 \text{ Gyr})$, and the interpretation of galaxy spectra at short $(\lambda < 3000 \text{ A})$. The sources believed to be responsible for the observed 'ultraviolet upturn phenomenon' (UVX) are Post-AGB (P-AGB), extreme horizontal branch (EHB) and AGB-Manqué (AGBM) stars. All of these have observational counterparts in old Galactic stellar populations, i.e. in globular clusters and in the Galactic field. The production of EHB stars depends on mass loss on the red giant branch, which is poorly understood, making the far-UV flux problematical as an indicator of the gross properties, such as the age, of a given galaxy. On the other hand, the longer, mid-UV wavelengths are radiated by stars near the main sequence turnoff which has well understood and predictable behavior. We discuss the current state of the comparison between theory and observation for the UVX phenomenon, and revisit the interpretation of the well-known UVX-Mg₂ correlation. In particular, we draw attention to the fact that the UVX appears not to be correlated with indices that measure the iron abundance, which has implications for models that explain the UV-Mg2 correlation as an abundance-driven effect. Finally, we note the potential utility of ultraviolet observations in distinguishing age and metallicity from galaxy spectral energy distributions.

1. Introduction

The ultraviolet upturn (often referred to as the "UVX phenomenon") from E/S0 galaxies and spiral galaxy bulges was first observed by the OAO-2 satellite in the late sixties (Code 1969). It consists of a far-UV $(\lambda < 2000 \text{ A})$ component in the spectra of all such galaxies so far observed. It is found to have similar radial structure to the optical light profile, and its amplitude is positively correlated with the Mg² line strength and with the velocity dispersion. This 'UVX component' of the population is now thought to consist of stars similar to the hot subdwarf sdB/sdO stars found in the Galactic field and some globular clusters. The characteristics of these stars coincide with those of theoretical models of extreme horizontal branch (EHB) and "AGB-manqué" stars. The former are core–helium-burning objects with very small hydrogen rich envelopes. The latter are their hot post-HB helium-burning progeny that have insufficiently massive envelopes to reach the asymptotic giant branch after the core helium supply is exhausted.

It is convenient to define 'far-ultraviolet' to refer to the spectral range $912 < \lambda < 1800 \text{ Å}$, and 'mid-ultraviolet' to mean $1800 < \lambda < 3000 \text{ Å}$. The observations are determined by the available detector technology: Caesium Iodide photocathodes used for the far-UV range have a sharp response cutoff at 1800\AA , while the mid-UV range detectors use Caesium Telluride which has little response below 3200\AA .

From the theoretical point of view, in old populations with turnoffs of spectral type $F5$ or later there is a strong break in the continuum around 2000 Å in synthetic spectral energy distributions (SEDs) for metallicities [Fe/H] \gtrsim − 0.5 (see §2.2). Thus, the SEDs of galaxies are generally composite in the mid-UV range, with the flux originating from the main-sequence (MS) and subgiant branch (SGB) and from hot, highly evolved stars that may be present. As we shall argue in §3, the mid-UV spectral range can in principle be decomposed into its two major contributors. Since the turnoff light is very sensitive to age and metallicity, the proper measurement and interpretation of this wavelength range holds promise as a source of population indicators for passively evolving elliptical galaxies.

This review is organized as follows. §2 describes the stellar sources of ultraviolet radiation in old stellar populations, both in the far- and the mid-UV. §3 discusses the comparison between theoretical expectations and some of the observations; further details of the observational record can be found in Dorman, O'Connell, & Rood 1995 (hereafter DOR95) and references therein. §4 briefly summarizes observations from the Galaxy and globular cluster system pertinent to understanding the UVX phenomenon, while §5 discusses the UVX phenomenon and the correlation with Mg_2 . The last section summarizes the potential for age/metallicity diagnostics in the mid-UV.

2. Theoretical Background

2.1 Horizontal Branch Morphology and the Production of Far-Ultraviolet Flux

The sources of far-UV radiation in old stellar populations that are most significant are those which are powered by stable nuclear reactions, i.e. hydrogen shell, helium core and helium shell nuclear fusion (for a discussion of other possible sources, see Greggio & Renzini 1990).

Evolutionary paths for the various types of hot objects are illustrated in Fig. 1. Further discussion on the details of the evolution can be found in Dorman, Rood, & O'Connell (1993, hereafter DRO93) Castellani & Tornambè (1991), and Brocato et al. (1990) amongst others.

a) Post-AGB stars: This is the 'classical' path for AGB stars crossing to the white dwarf cooling curve, from $T_{\text{eff}} \sim 3000$ to $\sim 10^5$ K. The lifetime in this phase ranges from a few times 10^4 yr to a few thousand years, decreasing strongly with the luminosity. The spectrum integrated over this

Figure 1. Schematic of the far-UV emitting stars in old stellar populations.

phase has a high characteristic temperature, and its total energy decreases with increasing P-AGB luminosity.

b) Hot HB stars: Stars that reach the HB with $T_{\text{eff}} \gtrsim 10,000 \,\text{K}$ can be formed for any metallicity, provided sufficient mass loss occurs on the red giant branch. Their lifetime is substantial, $\sim 10^8$ yr, with luminosities $\sim 10 50L_{\odot}$. For high metallicity nearly the entire mass of the envelope must be stripped in order to produce a hot star (see also D'Cruz et al. 1996), while at low Z models with substantial hydrogen-rich envelopes can be hot enough to radiate strongly in the far-UV. For sufficiently young systems $(t \sim 5 \,\text{Gyr})$ the amount of mass loss required to produce hot stars is much greater, so that hot HB stars are expected to be rare or not present. This qualitative statement unfortunately has no theory of mass loss available to make it quantitative.

After the core helium is exhausted, helium shell-burning is initiated. If the remaining envelope at this stage is sufficiently large ($> 0.05M_{\odot}$) the hot HB stars return to the AGB (i.e., they develop a convective exterior) as do their more massive red HB counterparts. They evolve through the thermally pulsing stage, finally becoming P-AGB stars and white dwarfs. Otherwise, they become Post-Early AGB stars or AGB-Manqué stars and are termed EHB stars. The EHB stars have envelope masses $\lesssim 0.05 M_\odot$, generally have insignificant hydrogen burning energy, and their effective temperatures range from about 20,000 to 37,000 K.

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c) AGB -Manqué and P-EAGB Stars: The core He-burning progeny of stars which have undergone extreme mass loss, these stars contribute more UV flux in the post-HB phase than do the classical P-AGB stars. The P-EAGB (Post-Early AGB) stars reach the "early" ascending AGB stage but not the thermally pulsing regime at $\log L \gtrsim 3.2$. They cross the HR diagram on tracks parallel to the P-AGB models, but at lower luminosity and with a characteristic timescale of 1 Myr. The AGB-Manqué stars are hot throughout the He-shell burning phase, with lifetimes typically $2 - 4 \times$ 10^7 yr (similar to the AGB itself), with $L \sim 100 - 500 L_{\odot}$.

We stress that for HB stars the total lifetime energy output varies by less than 50% for any abundance. This is because the mass of the helium core controlled by the He flash at the RGB tip—varies relatively little with abundance. Thus the helium core luminosity during the HB phase also varies little. The largest changes with composition occur with high helium enhancement $(Y \gtrsim 0.40)$, in which the hydrogen burning shell is hotter for the same envelope mass (Dorman 1992). The hydrogen burning luminosity is significant for a larger range in masses and the hydrogen energy production is greater. In contrast, the effect of including high Z values in the models with no concomitant increase in Y works to decrease slightly both the mass range and total flux radiated during the EHB lifetime.

Because of this relative invariance in total UV output, it is possible to constrain the UV-bright population rather tightly. We can regard UV/Optical colours such as $m_{\lambda}(1500) - V$ [hereafter $(15 - V)$] as indicators of the specific frequency of UV sources (the number present per unit luminosity). It also allows us to compare the UV properties of populations whose metallicities are vastly different but whose content may well be similar in age. The possibility of high Y abundance, which we have discussed elsewhere (DOR95), only adds at most a factor of two uncertainty in the number fractions of EHB stars deduced to be present (Dorman 1997a).

2.2 The Composite Nature of the mid-UV Radiation

The major contribution to the mid-UV range apart from the hot stellar component is from the stars close to the main-sequence turnoff, which is the next hottest population in a quiescent system. The importance of this spectral range and its potential appears to have first been stressed by Burstein et al. (1988), who noted that, if the UVX could be understood "... the $2600-3000$ Å spectrum may ultimately provide better constraints on age and composition than are available now from ground based data."

Figure 2 taken from Dorman & O'Connell (1996) shows the contributions from various parts of an old stellar population at wavelengths $\lambda < 4000 \,\mathrm{\AA}$, normalized to the V -band. In this diagram, the pre-He-flash stages of evolution (the "isochrone" contribution) is divided into three parts: the lower main sequence, with $T_{\text{eff}} < 5000 \text{ K}$ and $L < L_{\text{TO}}$; the turnoff region, with $T_{\text{eff}} > 5000 \text{ K}$, which includes a portion of the main sequence and of the subgiant branch; and lastly the RGB itself. The synthetic spectra in this figure assume a 10 Gyr population, solar metallicity, and a Salpeter IMF. The contribution from lower main sequence stars (not shown) is similar to that of the red HB stars. The possible hot components are represented by the integrated spectrum of an EHB star that evolves to an AGB-Manqué sequence (upper curve) and of a P-AGB star. These spectra are computed by assuming the entire post-RGB population passes through this evolutionary phase, and are weighted by the lifetime and the 'specific evolutionary flux,' defined as the number of stars entering the UV bright phase per unit time per unit magnitude of the parent population. The population synthesis scheme used here is described in DOR95.

Figure 2. The components of an old stellar population for $\lambda < 4000 \,\text{\AA}$. The "isochrone" component (1) is split into 3 parts: the red giant branch (2; $T_{\text{eff}} < 5000 \text{ K}$, $L > L_{\text{TO}}$), the turnoff region, $(3; T_{eff} > 5000 \text{ K})$ and the lower main sequence, which is similar in flux to the red $HB(4)$. The maximum possible contribution from EHB stars (including their AGB-Manqué progeny) (5) and P-AGB stars (6) are also shown. The models of late evolutionary stages are from DOR93, and the earlier stages were computed for the DOR95 study, together with synthetic fluxes from Kurucz 1992. Integrated fluxes are computed as described in DOR95.

Figure 3 shows the variation of mid-UV flux with metallicity. Plotted are spectra from 10 Gyr isochrones for $-2.26 <$ [Fe/H] < 0.58 with no synthetic hot component added. For comparison we show the observed spectra of the M31 bulge from IUE to which has been added a ground-based observation through a matched aperture (D. Calzetti, private communication; see also Worthey, Dorman & Jones 1996), and the Astronomical Netherlands Satellite (ANS) flux for the metal-poor globular cluster M13 (van Albada, de Boer, & Dickens 1981). The observations show that the difference in metallicity produces a large change in the flux level.

Figure 3. The variation with metallicity of the mid-UV spectral range. The models are computed as in figure 2, for $-2.26 <$ [Fe/H] < 0.58 at 10 Gyr. Also plotted are the IUE + optical spectrum of M31 (see Worthey, Dorman, & Jones 1996) and the ANS spectrum of M13.

3. Summary of Theory and Observation

Synthesis models constructed with isochrones plus astrophysically consistent horizontal branch populations of different morphologies (DOR95, Dorman & O'Connell 1997) predict various features of the UV radiation $(\lambda < 3200 \text{ Å})$. First, the strength of the far-UV component is proportional to the number of hot stars that are produced. In Fig. 2, the SED generated by the EHB component produces a bluest possible $(15 - V)$ colour close to 0. Since what we observe is $(15 - V) \gtrsim 2$, it follows that the fraction of EHB stars compared to the total HB population is \lesssim 15%. For solar or greater metallicity the rest of the HB stars will lie at the red end of the HB and eventually become P-AGB stars. Second, the EHB assumption implies a characteristic temperature for the UVX in the range $\sim 20,000 < T_{\text{eff}} < 37000 \text{ K}$. Brown, Ferguson & Davidsen (1995 and these proceedings) deduced characteristic temperatures from Hopkins Ultraviolet Telescope data between 20000 and 23000 K, and obtained the best model fits to the far-UV spectrum with a small range in EHB masses. The UV radiation in the galaxies is also observed to be radially concentrated, like the background population (O'Connell et al. 1992; Ohl & O'Connell 1997). Both of these imply an origin for the UV upturn in the background stellar population rather than due to young stars in discrete star forming regions.

The maximum possible theoretical contribution from P-AGB stars or P-EAGB stars gives insufficient UV flux $[(15 - V) \sim 3.6]$ to be responsible for the strongest UV upturns observed. In addition, since the P-AGB flux depends strongly on the mean luminosity of the AGB tip only, it is decoupled from the EHB output. A possible indicator of the relative importance of each may in principle be derived from the strength of the Lyman absorption lines which are much stronger in the cooler EHB sequences.

In the mid-UV, the contribution from the red giants is insignificant shortward of $\sim 3500 \text{\AA}$, and for $\lambda < 2000 \text{\AA}$ the hot stars are the only contributors. Hot stellar spectra are, however, relatively featureless in the mid-UV range. Thus the spectrum of a galaxy with a UV rising branch will have the 'signature' of the background turnoff population superposed, including the spectral features appropriate to a late $F/early G$ type population. The effect of the hot component on the mid-UV may therefore in principle be quantified and subtracted to yield population indicators (Burstein et al. 1988; Dorman & O'Connell 1996).

Because the mid-UV radiation from metal-poor populations is so much greater than for the metal-rich, they will have shallower ultraviolet slopes, as observed in the flatter UV spectra of globular clusters and in their measured $(15 - 25)$ colours (DOR95). The ratio of mid-UV to optical flux can therefore be used to constrain the metallicity spread in the population. The mid-UV colours of galaxies $[(25 - V) \gtrsim 3.5]$ appear to rule out fractions of metal-poor stars (i.e. [Fe/H] ≤ -1) greater than about 10% since the UV continuum of the isochrone component is at $(25 - V) \sim 2$, while at least 50% of the galaxy mid-UV continuum will be contributed by the hot component in a strong UVX galaxy. Further, for sufficiently old populations the short wavelength cutoff is a function of metallicity rather than age. Hence presence of significant flux shortward of 2000 Å in excess of what is implied by a hot component would suggest the presence of metal-poor stars.

Note that a relatively recent starburst, a few times 10^8 years old, could seriously affect the interpretation of the mid-UV flux. This possibility must also therefore be investigated: Worthey, Dorman & Jones (1996) discuss a potential indicator for any A star population. However, the mid-UV continuum level must give a lower bound to the age, since the presence of hot contaminants will make the spectral energy distribution appear younger than it is. This has immediate application in interpreting observations of rest-frame mid-UV continua of galaxies at significant redshift (Dunlop et al. 1996).

4. Old Galactic Stellar Populations and the Production of Hot Stars

Perhaps the strongest motivation for thinking that galaxies contain populations of EHB stars is that they appear to be a regular constituent of old stellar populations in our galaxy, in both the globular clusters and in the Galactic old disk population. This evidence is reviewed in Dorman (1997b). However, in many cases—particularly in the Galactic field, but also in some globular clusters—the HB population is not unimodal, and the most extreme blue stars in particular are separated from their cooler counterparts by a gap in temperature. Since the mass difference between cool ($T_{\text{eff}} \sim 5000 \text{ K}$) and hot stars in metal rich populations is theoretically only a few times $0.01 M_{\odot}$, the UV flux can vary enormously as a result of small changes in the total mass loss. The presence of gaps in the HB sequence, where they are statistically significant, either implies that more than one mass loss process is effective, or that a single process

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may lead to a bifurcation in HB properties. Thus the $(15 - V)$ colour of old stellar populations is not a simple function of age and metallicity. Models that attempt to derive ages from $(15 - V)$ colours assume simple analytical formulæ for the mass loss such as the Reimers (1975) "law," and that HB morphology becomes unambiguously bluer mainly as a result of age. Such models have been computed by Bressan *et al.* (1994); Park & Lee (1997) and Yi (1996). However, these models cannot provide necessary constraints on the ages of galaxies without a better understanding of the idiosyncrasies of stellar mass loss and the apparent variations between different stellar systems.

5. The UVX–Mg² Correlation Revisited

Since its discovery, the UVX phenomenon has continued to be a mystery with relatively few explanatory clues. While we have a viable hypothesis for the stars responsible for the phenomenon, we do not yet understand why the UVX phenomenon has the properties that it does. The most significant insight that has been found into the causes of the UVX was the discovery by Faber (1983) of its positive correlation with metallicity-sensitive indices. Burstein et al. (1988) then reported that this correlation was indeed present on the largest (and still today the most coherent and comprehensive) dataset on UV spectra of early-type galaxies. Burstein et al. noted the correlation between the UVX and the Lick optical absorption line index Mg_2 . They also noted a somewhat looser correlation with the galaxies' central velocity dispersions σ . However, the tightest correlation was with the Mg₂ index, which was thus held to be causal. Much theoretical work (Greggio & Renzini 1990; Horch, Demarque & Pinsonneault 1992; Bressan, Chiosi, & Fagotto 1994; Tantalo et al. 1996, Yi 1996) has attempted to explain the apparent correlation with Z.

The $(15 - V)$ vs Mg₂ diagram is reproduced in Fig. 4, which is adapted from DOR95 and includes for comparison the data from metal-poor Galactic globular clusters on the same axes. This diagram compares the UV flux from globulars whose UV sources we can resolve, measure, and thus use to constrain the theory with those of the galaxies. To our knowledge, the UV flux in the globulars shown is dominated by hot HB stars. The galaxies' specific UV flux, directly measured by the UV/optical colour, is seen to be of the same order of magnitude—albeit weaker—than that of the bluest clusters in which all of the HB stars contribute to the far-UV flux.

Explaining the $UVX-Mg_2$ correlation by invoking some feature of stellar evolution that is more effective in producing hot stars at high Z is attractive, but requires circumspection. DOR95 suggested that the $UVX-Mg₂$ correlation actually consists of three different behaviours: (a) "UVX-weak," of which M32 is so far the lone example. M32 is a Local Group dwarf elliptical with a mid-UV spectrum that possibly indicates a sizeable intermediate age population (but see Grillmair *et al.* 1996); (b) the bulk of the ellipticals, SO types and the spiral bulges that have $(15 - V) = 3 - 4$; and (c) the strong UVX systems, which are all giant ellipticals (we have included the slightly redder NGC 4889 in Coma as its measured UV/Optical color is probably underestimated compared to the

Figure 4. $(15 - V)$ colours of galaxies and Galactic globular clusters. The data are from the compilation in DOR95. Dashed lines indicate the division into three regimes referred to in the text. NGC numbers for some significant galaxies and clusters are shown.

nearer Virgo and Fornax objects since more of the galaxy is enclosed in the observing aperture). The correlation between the UVX and the line index is still present in group (b), but the relative scatter is large.

After the landmark paper by Burstein et al. appeared it became well- established that giant elliptical galaxies are overabundant in α -capture elements, including magnesium (Worthey, Faber, & Gonzalez 1992 and see the review in Davies 1996). The Mg₂ index, strongly correlated with $[Fe/H]$ in the globular clusters (Burstein et al. 1984) therefore does not serve as an indicator of Fe-peak elements in the super-solar metallicity regime. Also, the Mg2 index is found to be correlated with σ , whereas the same is not so for line indices such as Fe5270, Fe5330 that are designed to measure the iron abundance (Worthey 1996; Fisher, Franx, & Illingworth 1995).

Taken together, the implication is that there is no strong correlation between iron abundance and the UV upturn. This may be a significant factor in the theoretical modelling. As noted earlier, the potential increase in the ease at which EHB stars can be produced with increasing metallicity is, in fact, due to using high values of the helium abundance in the stellar models. The assumption of high Y follows from adopting $\Delta Y/\Delta Z \gtrsim 2.5$ for $Z > Z_{\odot}$. If additional data confirms that the UVX has no strong correlation with Fe indices these models can only be maintained if Y increases instead with the α elements¹. Finally, it should be recalled (DOR95) that there is little evidence for the behaviour of Y

¹ Note also that $\Delta Y/\Delta Z$ is determined largely from oxygen rather than iron abundances.

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with Z in the metal-rich regime; extrapolations from the slopes used in attempting to determine the primordial Y abundance may introduce gross overestimates of Y in the models.

These observations may be pointing towards a different understanding for the origin of the UVX. If we can extrapolate from the Galaxy, EHB stars are a normal constituent of old stellar populations. Their incidence is apparently higher in the cores of large ellipticals, perhaps those with distinct isophotal characteristics (Longo et al. 1989; see also Merritt, these proceedings).

While we are arguing that there is no direct interpretation of the far-UV component, it should also be stressed the UVX may be used empirically to help in the understanding of the integrated light at longer wavelengths. Observations in the rest-frame far-UV will constrain the effect of any hot component present and allow the measurement of the mid-UV continuum level that is sensitive to age and metallicity. Of course, these properties are difficult to distinguish cleanly. In the final section we briefly mention the potential that the mid-UV holds for insight into this well-known problem of separating them.

6. The Age/Metallicity Degeneracy and the Ultraviolet

The 'age-metallicity degeneracy' problem refers to the difficulty of separating age and metallicity effects between stellar populations. Both increasing Z and increasing age decrease the mean temperature of the stellar population. Further, RGB stars which contribute at least half the light in the V band are relatively insensitive to both. Worthey (1994) has stressed that optical broad band colours are particularly affected by this problem, and has isolated absorption line indices that are significantly more sensitive to either age or metallicity. However, broadband colours have significant advantages over line indices. They measure the continuum level of a source over a wider part of the spectrum, which makes accurate synthetic modelling much easier, and they can be observed to greater distance with sufficient S/N to provide usable diagnostics (*cf.* O'Connell 1996).

Using UV diagnostics to help resolve this problem has several important advantages. The mid-UV isolates the turnoff radiation, and thus is an indicator of the population that varies most strongly with the gross population properties. A similar goal underlies the use of $H\beta$ as an age indicator (Gorgas, Efstathiou & Arag´on-Salamanca 1990; Gonzalez 1993). The spectra of populations that are difficult to distinguish in the optical, where the spectra are dominated by red giants, can be very different in the UV. Fig. 5 shows the residuals between two single burst stellar population models that are similar at V (they differ by \lesssim 0.05 mag) but are easily distinguished for λ < 4000 Å.

A number of galaxies have now been studied in the rest-frame mid-UV from large ground based instruments. The determination of ages of stellar populations at $z > 1$ is an attractive cosmological tool because allows the most direct application of the well-established stellar evolution theory to cosmology. The best known example is the recent work of Dunlop et al. (1996) who obtained a spectrum of the radio galaxy LBDS 53W091. Comparison with synthetic spec-

Figure 5. Comparison between synthetic spectral energy distributions of 'degenerate' models. The difference between model fluxes computed for $[Fe/H] = 0$ at 16 Gyr has been subtracted from a 6 Gyr, $[Fe/H] = 0.5$, and is plotted against wavelength. The models are from the Crete CD-ROM database (Leitherer et al. 1996) contributed by Dorman & O'Connell, described in §6.5.

tra imply a lower bound to the age of 3.5 Gyr. The likelihood that much more similar data will become available in the future makes the proper understanding of the mid-UV continuum and its spectral features an important research goal.

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