Hot Subdwarfs in Binaries as the Source of the Far-UV Excess in Elliptical Galaxies

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Abstract. The excess of far-ultraviolet (far-UV) radiation in elliptical galaxies has remained one of their most enduring puzzles. In contrast, the origin of old blue stars in the Milky Way, hot subdwarfs, is now reasonably well understood: they are hot stars that have lost their hydrogen envelopes by various binary interactions. Here, we review the main evolutionary channels that produce hot subdwarfs in the Galaxy and present the results of binary population synthesis simulations that reproduce the main properties of the Galactic hot-subdwarf population. Applying the same model to elliptical galaxies, we show how this model can explain the main observational properties of the far-UV excess, including the far-UV spectrum, without the need to invoke ad hoc physical processes. The model implies that the UV excess is not a sign of age, as has been postulated previously, and predicts that it should not be strongly dependent on the metallicity of the population.

1. Introduction

One of the first major discoveries soon after the advent of UV astronomy was the discovery of an excess of light in the far-ultraviolet (far-UV) in elliptical galaxies (see the review by O’Connell 1999). This came as a complete surprise since elliptical galaxies were supposed to be entirely composed of old, red stars and not to contain any young stars that radiate in the UV. Since then it has become clear that the far-UV excess (or upturn) is not a sign of active contemporary star formation, but is mainly caused by an older population of helium-burning stars or their descendants with a characteristic surface temperature of 25,000 K (Ferguson et al. 1991), also known as hot subdwarfs or sdB stars. In recent years, it has become increasingly clear that their Galactic counterparts are predominantly produced by binary interactions (Maxted et al. 2001; Morales-Rueda et al. 2003; Lisker et al. 2005; Green 2008). Here, we first review the main evolutionary channels that produce hot subdwarfs in our Galaxy (see Han et al. 2002, 2003 for further details) and then apply this model to elliptical galaxies to show that these may also be able to account for their far-UV excess (Han, Podsiadlowski, & Lynas-Gray 2007).

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2. Evolutionary Channels for sdB Stars

To produce a helium-core-burning sdB star, it is necessary that the progenitor of the sdB star loses its hydrogen envelope just before reaching the tip of the first giant branch (FGB). In a single-star scenario for sdB stars (e.g., D'Cruz et al. 1996), this requires highly variable mass loss on the FGB, where some stars experience enhanced mass loss on the FGB (e.g., due to helium mixing driven by internal rotation [Sweigart 1997]) or at the helium flash itself; e.g., Han et al. (1994) showed that 1-$M_\odot$, solar-metallicity giants have only marginally bound envelopes near the tip of the FGB and that it is much easier to eject their envelopes at the helium flash than for their more massive counterparts with more tightly bound envelopes.

In a binary scenario, the progenitor of the sdB star typically has to fill its Roche lobe near the tip of the FGB to lose most of its hydrogen-rich envelope in the ensuing binary interaction. This can occur either through stable Roche-lobe overflow (RLOF) or in a common-envelope (CE) phase (Paczyński 1976). Alternatively, a hot subdwarf can be produced by the merger of two helium white dwarfs if helium is ignited in the merger product.

In order to ignite helium in the core and therefore have a long-lived subdwarf phase lasting $\sim 10^8$ yr, one has to distinguish whether the progenitor develops a degenerate helium core or not. Relatively low-mass stars ($M_0 \lesssim 2M_\odot$ for models with moderate convective overshooting) develop degenerate helium cores, and helium will only be ignited if the core mass at the beginning of the mass-transfer phase is quite close to the core mass at the helium flash (typically within 0.025 $M_\odot$). This core mass range corresponds to a range of red-giant radii $\Delta \log R \simeq 0.07$, which can be related to a range of initial orbital periods at which a typical giant in a binary fills its Roche lobe of $\Delta \log P \simeq 0.1$. For a canonical binary orbital-period distribution, this implies that $\sim 1\%$ of all stellar systems in the appropriate mass range will lose their envelopes at this stage by binary interactions. This corresponds to a characteristic birthrate for sdB star in the Galaxy of $10^{-2}$ yr$^{-1}$, consistent with previous observational estimates (e.g., Heber 1986).

Stars with an initial mass $M_0 \gtrsim 2M_\odot$ ignite helium under non-degenerate conditions, and mass loss can occur at any time after the main-sequence phase. In contrast to their lower-mass counterparts which have a sharply peaked sdB mass distribution around 0.46 $M_\odot$, these produce a much wider distribution of sdB star masses, which can be as low as 0.32 $M_\odot$.

2.1. Common-Envelope Channels

In the CE channel (see Figure 1), the progenitor of the sdB star is a giant that fills its Roche lobe near the tip of the FGB and experiences dynamical mass transfer. This generally requires that the mass ratio of the donor star to the secondary, the accreting component, is larger than $\sim 1.2$. In this case, the secondary is unable to accrete all of the transferred matter and starts to fill and ultimately overfill its own Roche lobe. This leads to the formation of a common envelope surrounding both stars. Inside the common envelope, the core of the giant and the secondary form an immersed binary. Because of friction with the envelope, these two components spiral towards each other until enough orbital...
energy is released to eject the envelope (Paczyński 1976). This ends the spiral-in phase and leaves a much closer binary with an orbital period typically between 0.1 and 10 d, consisting of the core of the giant and the secondary.

In general, the CE phase can be either the first or the second mass-transfer phase in binary. In the former case, the companion of the sdB star is expected to be a normal star, most likely a main-sequence star, while in the latter case it is a helium white dwarf. In the best-fit model of Han et al. (2003), the birthrates of sdB stars in the CE channel are $\sim 0.7 \times 10^{-2}$ yr$^{-1}$ for sdB stars with normal stellar companions and $\sim 0.4 \times 10^{-2}$ yr$^{-1}$ for sdB stars with white-dwarf companions.
2.2. The Stable Roche-Lobe Overflow (RLOF) Channel

The main difference in the stable RLOF channel (e.g., Mengel, Norris, & Gross 1976) is that mass transfer (the left panel in Figure 2) is stable and does not lead to a common-envelope and spiral-in phase. Because of the mass transfer, the binary system tends to widen. The typical final orbital period is 100 to 500 d (for \( M_0 < 2 M_\odot \)), but can be as short as a few days for \( M_0 > 2 M_\odot \). Since in the latter case, the companions are expected to be A stars, it is likely that these systems are selected against in most hot subdwarf surveys.

2.3. The Merger Channel

In the merger channel (Webbink 1984; Iben & Tutukov 1986), the lighter of two helium white dwarfs is dynamically disrupted when it fills its Roche lobe. The requires that the initial orbital period of the helium white dwarf binary is close enough (\( \lesssim 8 \) hr) that gravitational radiation can bring the system into contact. Most of the mass of the disrupted star will subsequently be accreted by the more massive white dwarf which at a certain critical mass ignites helium and becomes

Figure 2. Stable Roche-lobe channel (left) and single-star/merger channels (right) for the formation of sdB stars.
a single sdB star. The distribution of sdB stars for the merger channel is quite broad with a range from 0.4 to 0.65 $M_\odot$. In our best-fit model, the birthrate of sdB stars in the merger channel is $0.8 - 1.6 \times 10^{-2}$ yr$^{-1}$, i.e., is comparable to the CE channels.

2.4. The Population of sdB Stars

Figure 3 compares the results of binary population synthesis (BPS) simulations (small dots) for the best-fit model of Han et al. (2003) with the observed distribution (large symbols) in the $T_{\text{eff}}$–log $g$ diagram, where the top panel does not include observational selection effects, while the bottom panel does. Overall the distribution of observed stars is quite well reproduced. One of the main conclusions of these simulations is that the birthrates of the three main
evolutionary channel (CE channel, RLOF channel and the merger channel) are of comparable importance, consistent with recent studies (see Green 2008).

3. The UV Excess in Elliptical Galaxies

The origin of this population of hot, blue stars in an otherwise red population has, however, remained a major mystery (Greggio & Renzini 1990). Two scenarios, referred to as the high- and the low-metallicity scenario, have been advanced. In the low-metallicity model (Lee 1994), it is argued that these hot subdwarfs originate from a low-metallicity population of stars which produce very blue helium core-burning stars. This model tends to require a very large age of the population (in fact, larger than the generally accepted age of the Universe); it is also not clear whether the population is sufficiently blue to account for the observed UV color. Moreover, the required low metallicity appears to be inconsistent with the large metallicity inferred for the majority of stars in elliptical galaxies (Terlevich & Forbes 2002). In contrast, the high-metallicity model (Bressan, Chiosi, & Fagotto 1994; Yi, Demarque, & Kim 1997) assumes a relatively high metallicity – consistent with the metallicity of typical elliptical galaxies (∼1–3 times the solar metallicity) – and an associated enhancement in the helium abundance and, most importantly, postulates an enhanced and variable mass-loss rate on the red-giant branch, so that a fraction of stars lose most of their hydrogen-rich envelopes before igniting helium in the core (Yi et al. 1997; Dorman, O’Connell, & Rood 1995).

Both models are quite ad hoc: there is neither observational evidence for a very old, low-metallicity sub-population in elliptical galaxies, nor is there a physical explanation for the very high mass loss required for just a small subset of stars. Furthermore, both models require a large age for the hot component and therefore predict that the UV excess declines rapidly with redshift. This is not consistent with recent observations, e.g. with the Hubble Space Telescope (HST) (Brown et al. 2003). In particular, the recent survey with the GALEX satellite (Rich et al. 2005) showed that the UV excess, if anything, may increase with redshift. Indeed, the wealth of observational data obtained with GALEX is likely to revolutionize our understanding of elliptical galaxies. While Burstein et al. (Burstein et al. 1988) appeared to have found a correlation between the UV-upturn and metallicity in their sample of 24 quiescent elliptical galaxies, which could support the high-metallicity scenario, this correlation has not been confirmed in the much larger GALEX sample (Rich et al. 2005), casting serious doubt on this scenario.

Both models ignore the effects of binary evolution. Since we know that in our galaxy most of the far-UV light from old stars comes from hot subdwarfs in binaries, it is only reasonable to assume that they will also contribute in other galaxies. Indeed, it would be implausible to assume that the stellar populations in other galaxies were less complex than in our own.

4. The Model

To quantify the importance of the effects of binary interactions on the spectral appearance of elliptical galaxies, we have performed the first population synthe-
Figure 4. The evolution of the far-UV spectrum with time for a single population where all stars formed at the same time. The flux $f_\lambda$ is scaled relative to the visual flux ($f_V$).
Figure 5. Two-population fit to the far-UV spectrum of NGC 3379 for different assumptions about the fraction of the young population ($f$) and the amount of interstellar extinction (solid curves). The grey histogram represents the HUT observations by Brown et al. (1997). The theoretical models assume the dust extinction model of Calzetti et al. (2000).

sis study of galaxies that includes binary evolution (see also Bruzual & Charlot 1993; Worthey 1994; Zhang, Li, & Han 2005). It is based on a binary population model described above (Han et al. 2002, 2003) that has been calibrated to reproduce the short-period hot subdwarf binaries in our own Galaxy that make up the majority of Galactic hot subdwarfs. The population synthesis model follows the detailed time evolution of both single and binary stars, including all binary interactions, and is capable of simulating galaxies of arbitrary complexity, provided the star-formation history is specified. To obtain galaxy colors and spectra, we have calculated detailed grids of spectra for hot subdwarfs using the ATLAS9 (Kurucz 1992) stellar atmosphere code. For the spectra and colors of single stars with hydrogen-rich envelopes, we use the comprehensive BaSeL library of theoretical stellar spectra (Lejeune, Cuisinier, & Buser 1997, 1998).

5. Results and Discussion

Figure 4 shows our simulated evolution of the far-UV spectrum of a galaxy in which all stars formed at the same time, where the flux has been scaled relative to the visual flux (between 5000 and 6000 Å) to reduce the dynamical range. At
Figure 6. Evolution of far-UV properties [the slope of the far-UV spectrum, \( \beta_{\text{FUV}} \), versus \((1550 - V)\)] for a two-population model of elliptical galaxies. The age of the old population is assumed to be 12 Gyr (filled squares, filled triangles, or filled circles) or 5 Gyr (open squares, open triangles, or open circles). The mass fraction of the younger population is denoted as \( f \) and the time since the formation as \( t_{\text{minor}} \) [plotted in steps of \( \Delta \log(t) = 0.025 \)]. Note that the model for \( f = 100\% \) (the dotted curve) shows the evolution of a simple stellar population with age \( t_{\text{minor}} \). The legend is for \( b_{\text{FUV}} \), which is the fraction of the UV flux that originates from hot subdwarfs resulting from binary interactions. The effect of internal extinction is indicated in the top-left corner, based on the Calzetti internal extinction model with \( E(B - V) = 0.1 \) (Calzetti et al. 2000). For comparison, we also plot galaxies with error bars from HUT (Brown et al. 1997) and IUE observations (Burstein 1988). The galaxies with strong signs of recent star formation are denoted with an asterisk (NGC 205, NGC 4742, NGC 5102).

Early times the far-UV flux is dominated by the contribution from single young stars. Binary hot subdwarfs become important after about 1.1 Gyr, which corresponds to the evolutionary timescale of a \( 2 M_\odot \) star and soon start to dominate completely. After a few Gyr the spectrum no longer changes appreciably.

There is increasing evidence that many elliptical galaxies had some recent minor star-formation events (Kaviraj et al. 2007; Schawinski et al. 2007), which also contribute to the far-UV excess. To model such secondary minor starbursts, we have constructed two-population galaxy models, consisting of one old, dominant population with an assumed age \( t_{\text{old}} \) and a younger population of variable age, making up a fraction \( f \) of the stellar mass of the system. In order to illustrate the appearance of the galaxies for different lookback times (redshifts), we adopted two values for \( t_{\text{old}} \), of 12 Gyr and 5 Gyr, respectively; these values correspond to the ages of elliptical galaxies at a redshift of 0 and 0.9, respectively.
assuming that the initial starburst occurred at a redshift of 5 and adopting a standard ΛCDM cosmology with \( H_0 = 72 \text{ km/s/Mpc} \), \( \Omega_M = 0.3 \) and \( \Omega_\Lambda = 0.7 \). Our spectral modelling shows that a recent minor starburst mostly affects the slope in the far-UV SED. We therefore define a far-UV slope index \( \beta_{\text{FUV}} \) as \( f_\lambda \sim \lambda^{\beta_{\text{FUV}}} \), where \( \beta_{\text{FUV}} \) is fitted between 1075 Å and 1750 Å. This parameter was obtained from our theoretical models by fitting the far-UV SEDs and was derived in a similar manner from observed far-UV SEDs of elliptical galaxies (Burstein et al. 1988; Brown et al. 1997), where we excluded the spectral region between 1175 Å and 1250 Å, the region containing the strong Lyα line. In order to assess the importance of binary interactions, we also defined a binary contribution factor \( b = F_b/F_{\text{total}} \), where \( F_b \) is the integrated flux between 900 Å and 1800 Å radiated by hot subdwarfs produced by binary interactions, and \( F_{\text{total}} \) is the total integrated flux between 900 Å and 1800 Å. Figure 6 shows the far-UV slope as a function of UV excess, a potentially powerful diagnostic diagram which illustrates how the UV properties of elliptical galaxies evolve with time in a dominant old population with a young minor sub-population. For comparison, we also plot observed elliptical galaxies from various sources. Overall, the model covers the observed range of properties reasonably well. Note in particular that the majority of galaxies lie in the part of the diagram where the UV contribution from binaries is expected to dominate (i.e. where \( b > 0.5 \)).

The two-component models presented here are still quite simple and do not take into account, e.g., more complex star-formation histories, possible contributions to the UV from AGN activity, non-solar metallicity or a range of metallicities. Moreover, the binary population synthesis is sensitive to uncertainties in the binary modelling itself, in particular the mass-ratio distribution and the condition for stable and unstable mass transfer (Han et al. 2003). We have varied these parameters and found that these uncertainties do not change the qualitative picture, but affect some of the quantitative estimates.

Despite its simplicity, our model can successfully reproduce most of the properties of elliptical galaxies with a UV excess: e.g., the range of observed UV excesses, both in \((1550 - V)\) and \((2000 - V)\) (e.g., Deharveng, Boselli, & Donas 2002), and their evolution with redshift. The model predicts that the UV excess is not a strong function of age, and hence is not a good indicator for the age of the dominant old population, as has been argued previously (Yi et al. 1999), but is very consistent with recent GALEX findings (Rich et al. 2005). We typically find that the \((1550 - V)\) color changes rapidly over the first 1 Gyr and only varies slowly thereafter. This also implies that all old galaxies should show a UV excess at some level. Moreover, we expect that the model is not very sensitive to the metallicity of the population since metallicity does not play a significant role in the envelope ejection process (although it may affect the properties of the binary population in more subtle ways).

Our model is sensitive to both low levels and high levels of star formation. It suggests that elliptical galaxies with the largest UV excess had some star formation activity in the relatively recent past (\( \sim 1 \) Gyr ago). AGN and supernova activity may provide supporting evidence for this picture, since the former often appears to be accompanied by active star formation, while supernovae, both core collapse and thermonuclear, tend to occur mainly within \( 1 - 2 \) Gyr after a starburst in the most favoured supernova models.
The modelling of the UV excess presented in this study is only a starting point: with refinements in the spectral modelling, including metallicity effects, and more detailed modelling of the global evolution of the stellar population in elliptical galaxies, we suspect that this may become a powerful new tool helping to unravel the complex histories of elliptical galaxies that a long time ago looked so simple and straightforward.

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