Binary Stars as the Source of the Far-UV Excess in Elliptical Galaxies

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Summary. The discovery of an excess of light in the far-ultraviolet (UV) spectrum in elliptical galaxies was a major surprise in 1969. While it is now clear that this UV excess is caused by an old population of hot helium-burning stars without large hydrogen-rich envelopes rather than young stars, their origin has remained a mystery. Here we show that these stars most likely lost their envelopes because of binary interactions, similar to the hot subdwarf population in our own Galaxy. This has major implications for understanding the evolution of the UV excess and of elliptical galaxies in general. In particular, it implies that the UV excess is not a sign of age, as had 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 [1]). 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 caused by an older population of helium-burning stars or their descendants with a characteristic surface temperature of 25,000 K [2], also known as hot subdwarfs.

The origin of this population of hot, blue stars in an otherwise red population has, however, remained a major mystery [3]. Two scenarios, referred to as the high- and the low-metallicity scenario, have been advanced. In the low-metallicity model [4], 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 [5]. In contrast, the high-metallicity model [6, 7] assumes a relatively high
metallicity – consistent with the metallicity of typical elliptical galaxies (\(\sim 1 – 3\) 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 [7, 8].

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) [9]. In particular, the recent survey with the GALEX satellite [10] 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. [11] 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 [10], casting serious doubt on this scenario.

Both models ignore the effects of binary evolution. On the other hand, hot
subdwarfs have long been studied in our own Galaxy [12], and it is now well
established [13] that the vast majority of (and quite possibly all) Galactic hot subdwarfs are the results of binary interactions where a star loses all of its
envelope near the tip of the red-giant branch by mass transfer to a companion
star or by ejecting it in a common-envelope phase, or where two helium white
dwarfs merge to produce a single object (see [14, 15] for references and details).
In all of these cases, the remnant star ignites helium and becomes a hot
subdwarf. The key feature of these binary channels is that they provide the
missing physical mechanism for ejecting the envelope and for producing a hot
subdwarf. Moreover, since it is known that these hot subdwarfs provide an
important source of far-UV light in our own Galaxy, it is not only reasonable
to assume that they will also contribute significantly to the far-UV in elliptical
galaxies, but is in fact expected.

2 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 synthesis study of galaxies that includes binary evolution (see also [16, 17, 18]).
It is based on a binary population model [14, 15] 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 \[13\]. 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 \[19\] 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 \[20, 21\].

3 Results and Discussion

Fig. 1. 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 1 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\(\text{Å}\)) to reduce the dynamical range. At early times the far-UV flux is dominated by the contribution
Fig. 2. 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 \( E(B-V) = 0.1 \) [27]. For comparison, we also plot galaxies with error bars from HUT [22] and IUE observations [11]. The galaxies with strong signs of recent star formation are denoted with an asterisk (NGC 205, NGC 4742, NGC 5102).

There is increasing evidence that many elliptical galaxies had some recent minor star-formation events [23, 24], 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 $\Lambda$CDM 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 1075Å and 1750Å. 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 [11, 22], where we excluded the spectral region between 1175Å and 1250Å, the region containing the strong Ly$\alpha$ line.

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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 [15]. 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. [25]), 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 [26], but is very consistent with recent GALEX findings [10]. 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 (∼ 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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