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UV UPTURN OF ELLIPTICAL GALAXIES

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Abstract. We investigate the UV upturn phenomenon of elliptical galaxies by applying the binary model of hot subdwarfs of Han et al. (2002, 2003). Preliminary results show that the model provides a natural explanation for the UV upturn phenomenon and that the model could be used to detect low level recent star formation.

Key words: galaxies: elliptical – ultraviolet: galaxies – stars: binaries: close – stars: subdwarfs

1. INTRODUCTION

For old stellar populations, such as giant elliptical galaxies, far-UV radiation was expected to be almost completely dark. However, this is not the case. As surprisingly discovered by *Orbiting Astronomical Observatory 2* (OAO-2) mission in 1969, there exists a flux increase in spectral energy distributions of early-type galaxies from 2000 to 1200 Å, known as UV upturn (also referred as UV excess, UV rising-branch, UV rising flux, UVX) (see the review by O'Connell 1999). The origin of the UV upturn remained a mystery for many years ever since (see, e.g., Kjærgaard 1987). Ferguson et al. (1991), Dorman et al. (1995) and Brown et al. (1995, 1997) identified that UV upturn is mainly from extreme horizontal branch (EHB) stars. Brown et al. (2000) resolved hot HB stars for the first time in an elliptical galaxy (the core of M 32).

EHB stars are core-helium burning stars with very thin hydrogen envelopes ($M_{\rm env} \leq 0.02 M_\odot$). They are the major source of far UV radiation in the evolutionary population synthesis study of giant elliptical galaxies. There are two schools of thought about the UV upturn, metal-poor school (Lee 1994; Park & Lee 1997) and metal-rich school (Bressan et al. 1994, 1996; Tantalo et al. 1996; Yi et al. 1995, 1997a, 1997b, 1998). Both schools adopt the formation channel of EHB stars from single stellar evolution, in which stellar wind mass-loss near the tip of the first giant branch (FGB) may strip off a giant's envelope and leave an almost bare helium core (e.g., D'Cruz et al. 1996).

The metal-poor school ascribes the UV-upturn to an old metal-poor population (the metal-poor tail of the wide metallicity distribution). An uncomfortably large age (~ 20 Gyr) is required to explain observations. In the metal-rich school, the UV-upturn results from the metal-rich population of giant elliptical galaxies. In order to fit observations, some assumptions need to be made, i.e., helium enrichment parameter $\Delta Y/\Delta Z > 2.5$, a fine-tuning of Reimer's mass-loss coefficient and its dependence on metallicity, a metallicity of 1–3 $Z_\odot$ and an age usually larger than 10 Gyr. Some of the assumptions are not justified.

In both schools, the formation of EHB stars is due to stellar wind mass-loss near the tip of the FGB, and therefore there is a sudden onset of the formation of EHB stars when a stellar population evolves. In other words, the UV upturn of elliptical galaxies declines rapidly with redshift. However, this is not the case, as shown by HST observations of Brown et al. (1998, 2000, 2003).

However, more than half of hot subdwarfs are found in binaries observationally (e.g., Maxted et al. 2001). Han et al. (2002, 2003) therefore proposed a binary model for the formation of EHB stars (or hot subdwarfs). In the model, there are three channels for the formation of hot subdwarfs, i.e., common envelope ejection for hot subdwarf binaries with short orbital periods, stable Roche lobe overflow for hot subdwarfs with long orbital periods, and merger of helium white dwarfs to form single hot subdwarfs. The model can explain the main observational characteristics of hot subdwarfs, in particular their distributions in the orbital period vs. minimum companion mass diagram and in the effective temperature vs. surface gravity diagram, their distributions of orbital period and mass function, their binary fraction and the fraction of hot subdwarf binaries with white dwarf (WD) companions, their birth rates and their space density.

In this paper we apply the binary model of Han et al. (2002, 2003) to the study of UV upturn and give the preliminary results. A more systematic and comprehensive study will be published elsewhere.

2. THE APPROACH

Han et al. (1994, 1995a, 1995b, 1998, 2003) developed a binary population synthesis (BPS) code, with which millions of stars (including binaries) can be evolved simultaneously from the zero-age main sequence (ZAMS) to white dwarfs or supernova explosion. The code can simulate in a Monte Carlo way the formation of many interesting stellar objects, such as type Ia supernovae, cataclysmic variables, double degenerates, barium stars, etc.

We incorporate the binary hot subdwarf model of Han et al. (2002, 2003) into the BPS code so that we can carry out Monte Carlo simulations and obtain the hot subdwarf population and its evolution. In the simulations, we adopt a metallicity of $Z = 0.02$, the critical mass ratio $q_{\rm crit} = 1.5$ for stable Roche lobe overflow on first giant branch (FGB) or asymptotic giant branch (AGB), common envelope ejection efficiency $\alpha_{\rm CE} = 0.75$ and thermal contribution to the ejection $\alpha_{\rm th} = 0.75$ (see section 7.4 of Han et al. 2003 for details). In addition, the simulations also require as input the star formation rate (SFR), the initial mass function (IMF) of the primary, the initial mass-ratio distribution and the distribution of initial orbital separations as follows.

(1) The SFR is taken to be a single burst.

(2) A simple approximation to the IMF of Miller & Scalo (1979) is used; the primary mass is generated with the formula of Eggleton, Fitchett & Tout (1989)

$$M_1 = \frac{0.19X}{(1-X)^{0.75} + 0.032(1-X)^{0.25}}, \tag{1}$$

where X is a random number uniformly distributed between 0 and 1. The adopted ranges of primary masses are 0.8 to $100.0\,M_\odot$. The studies by Kroupa, Tout & Gilmore (1993) and Zoccali et al. (2000) support this IMF.

(3) We take a constant mass-ratio distribution in the current study,

$$n(1/q) = 1, \qquad 0 \leq 1/q \leq 1, \tag{2}$$

where $q = M_1/M_2$.

(4) We assume that all stars are members of binary systems and that the distribution of separations is constant in $\log a$ (a is the separation) for wide binaries and falls off smoothly at close separations:

$$an(a) = \begin{cases} \alpha_{\rm sep}(\frac{a}{a_0})^m, & a \leq a_0; \\ \alpha_{\rm sep}, & a_0 < a < a_1, \end{cases} \tag{3}$$

where $\alpha_{\rm sep} \approx 0.070$, $a_0 = 10\,R_\odot$, $a_1 = 5.75 \times 10^6\,R_\odot = 0.13\,{\rm pc}$ and $m \approx 1.2$. This distribution implies that there is an equal number of wide binary systems per logarithmic interval and that approximately 50 per cent of stellar systems are binary systems with orbital periods less than 100 yr.

In order to convolve the simulation result into colors or spectral energy distribution (SED), we adopt the latest version of BaSeL library (see Lejeune et al 1997, 1998 for a description), which gives the colors and SEDs of stars with a wide range of metallicity Z, surface gravity $\log g$ and effective temperature $T_{\rm eff}$. The library does not cover the surface gravity range for hot subdwarfs, and we therefore calculated emergent fluxes for solar metallicity hot subdwarfs using plane-parallel static model stellar atmospheres computed with ATLAS9 (Kurucz 1992) and adopting the assumption of local thermodynamic equilibrium, and the range for $\log g$ is 5.0 to 7.0 with a spacing of $\Delta \log g = 0.2$, the range for $T_{\rm eff}$ is 10 000 K to 40 000 K with $\Delta T = 1000$ K.

3. RESULTS AND DISCUSSION

In our investigation, we evolve a simple stellar population (SSP), in which all the stars have the same metallicity and the same age, or a mixed stellar population (MSP) which consists of two SSPs, a major one and a minor one. The major population has solar metallicity and an age of 10 Gyr, while the minor one has a solar metallicity and an age t. The minor population fraction f is the ratio of minor population mass to the total mass of the MSP, and $f = 100\,\%$ means the MSP is actually a SSP with an age t.

Figure 1 is a comparison between the UV spectrum from our model and that of M 49 from the Hopkins Ultraviolet Telescope (HUT) (from Brown et al. 1997). The model is a solar metallicity MSP with a total stellar mass of $4.7 \times 10^{10} M_\odot$ and a major population age of 10 Gyr. The minor population fraction is $f = 0.28\,\%$, and the minor population has an age of 0.5 Gyr. Actually we fixed the age of the major population according to local galaxy ages derived by Terlevich & Forbes (2002) and the minor population fraction, and obtained the best fit when the minor population age is 0.5 Gyr (the details of the fitting process will be described in another publication). The fraction of $f = 0.28\,\%$ is below the detecting limit for recent star formation. We see that the fit is satisfactory.

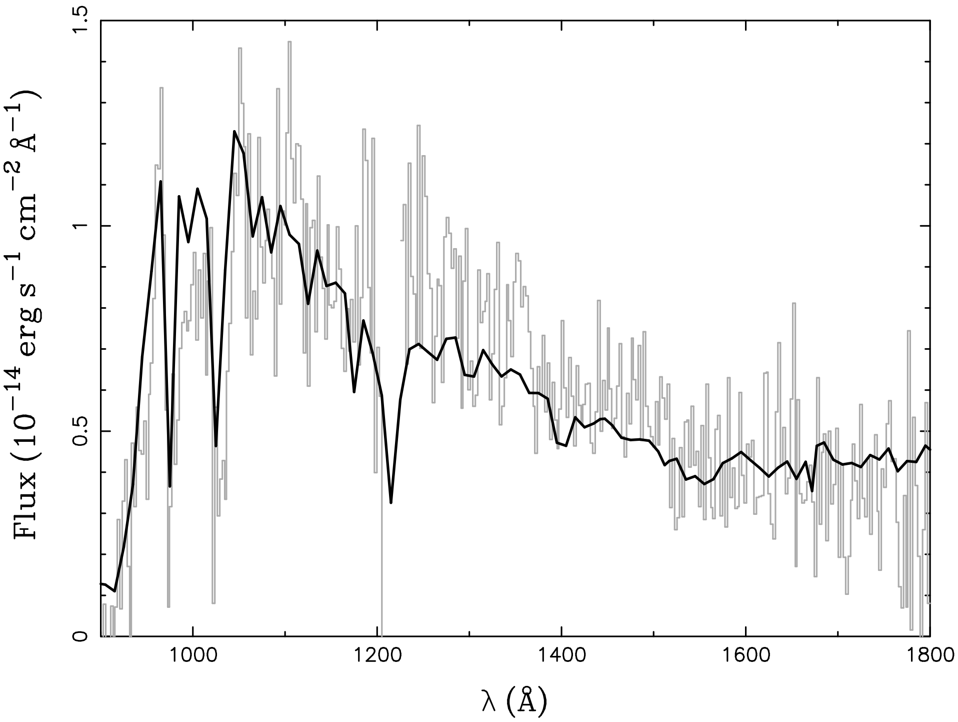

Fig. 1. A fit to the UV spectrum of elliptical galaxy M 49 obtained using the Hopkins Ultraviolet Telescope (HUT) (taken from Brown et al. 1997). The HUT data are shown by the grey histogram, while the thick solid line is from our model.

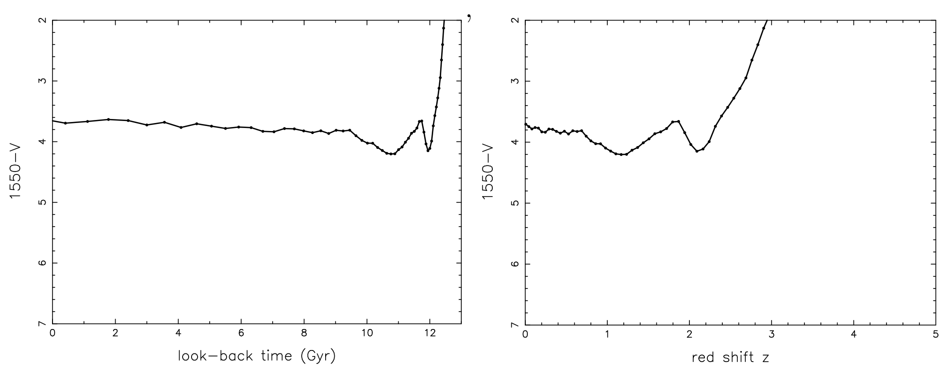

Fig. 2. The UV-upturn vs. look-back time (the left panel) and the UV-upturn vs. redshift (the right panel) from our model.

The magnitude of UV-upturn is defined by Burstein et al. (1988) as *1550–V* = –2.5 $\log(f_{1550}/f_V)$, where f_{1550} is the energy flux at 1550 Å and f_V – the flux in the V passband. Figure 2 is the UV-upturn versus the look-back time or the redshift for a SSP. The look-back time is defined as $t_{\rm L} = 13\,{\rm Gyr} - t_{\rm SSP}$, where $t_{\rm SSP}$

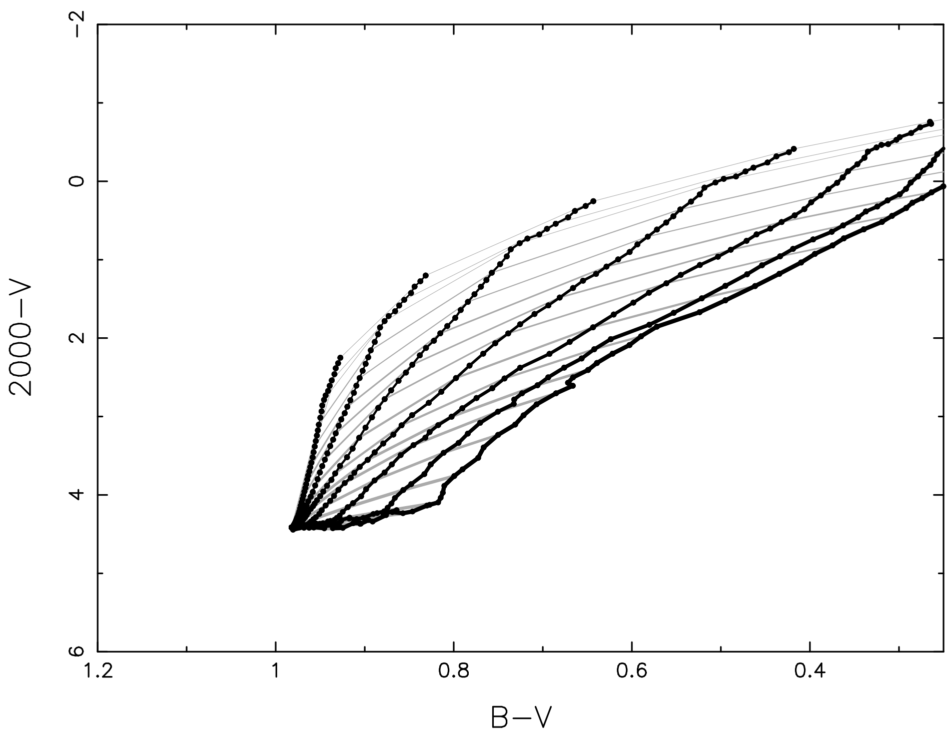

Fig. 3. *2000–V* vs. B–V for a mixed stellar population composed of a major and a minor population. The major population is with solar metallicity and with an age of 10 Gyr. The grey lines from top to bottom are for minor population age of $\log{(t/\mathrm{Gyr})} = -1.0$, –0.9, –0.8, –0.7 . . ., the dark solid lines from left to right are for minor population fractions of 0.1 %, 0.32 %, 1 %, 3.2 %, 10 %, 32 % and 100 %, while 100 % means that the mixed population is actually a single population (i.e., minor population only).

is the age of the SSP. We also convert the look-back time to redshift by adopting a flat universe and a Hubble time of 13.7 Gyr. As we see from Brown et al. (2003), UV-upturn does not depend much on redshift, and Figure 2 is consistent with the observations. Lee et al. (2005) tried to explain UV upturn-redshift relation by assuming that the post AGB (PAGB) mass decreases with redshift. However, the mass should increase with redshift from standard stellar evolution theory.

Figure 3 is the diagram of *2000* – V vs. $B - V$ for a solar metallicity MSP with a major population of 10 Gyr and a minor population of varying age and fraction. The figure can be used to explain the observation of far-ultraviolet emission of early-type galaxies (see Fig. 2 of Deharveng et al. 2002).

Figure 4 is the diagram of $FUV-NUV$ vs. $FUV-r$, where FUV and NUV are magnitudes in the FUV and NUV passbands of the *Galaxy Evolution Explorer* (GALEX) and r is the magnitude in the r passband of the Sloan Digital Sky Survey (SDSS). If we compare our result to the systematics of the UV-upturn in a GALEX/SDSS sample of early-type galaxies (Fig. 3 of Rich et al. 2005), we find that the red-quiescent early-type galaxies in their sample have low level recent star formation.

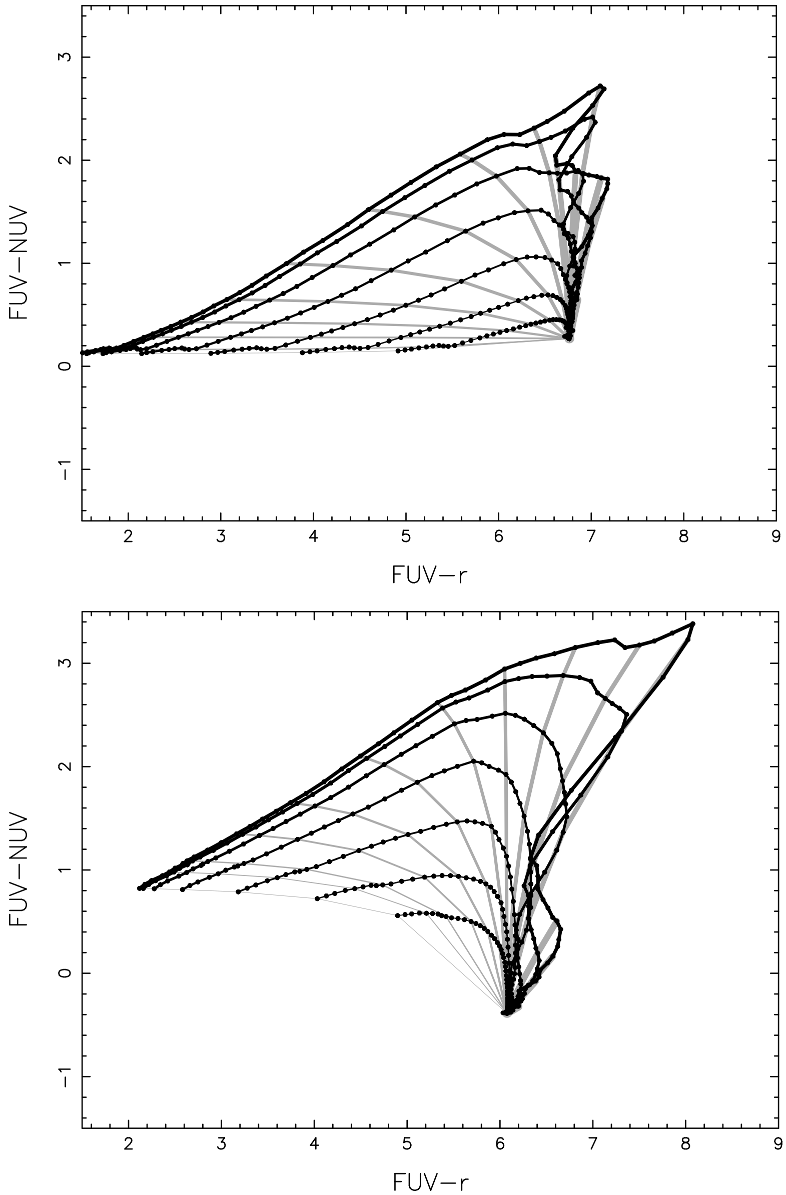

Fig. 4. $FUV-NUV$ vs. $FUV-r$ for a mixed stellar population composed of a major and a minor population. The major population is with solar metallicity and with an age of 10 Gyr. The grey lines from bottom-left to top-right are for minor population age of $\log(t/\mathrm{Gyr}) = -1.0$, –0.9, –0.8, –0.7 ..., the dark solid lines from bottom to top are for minor population fractions of 0.1 %, 0.32 %, 1 %, 3.2 %, 10 %, 32 % and 100 %, while 100 % means that the mixed population is actually a single population (i.e., minor population only). The top panel is for population at redshift $z = 0$, while the bottom panel is for $z = 0.2$.

4. CONCLUSIONS

We conclude that the binary model of hot subdwarfs of Han et al. (2002, 2003) is needed to understand the UV-upturn phenomenon of elliptical galaxies. Our model could be a useful tool in finding low level recent star formation.

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