Diffuse Gas in Galaxies Sheds New Light on the Origin of Type Ia Supernovae

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ABSTRACT

We measure the strength of He II λ4686 nebular emission in passively evolving (“retired”) galaxies, aiming to constrain their populations of hot accreting white dwarfs (WDs) in the context of the single degenerate (SD) scenario of Type Ia supernovae (SNe Ia). In the SD scenario, as a WD burns hydrogen-rich material accreted from a companion star, it becomes a powerful source of ionizing UV emission. If significant populations of such sources exist in galaxies, strong emission in the recombination lines of He II should be expected from the interstellar medium. To explore this conjecture, we select from the Sloan Digital Sky Survey ∼11 500 emission line galaxies with stellar ages >1 Gyr showing no signs of AGN activity and co-add their spectra in bins of stellar population age. For the first time, we detect He II λ4686 nebular emission in retired galaxies and find it to be significantly weaker than that expected in the SD scenario, especially in the youngest age bin (1−4 Gyr) where the SN Ia rate is the highest. Instead, the strength of the observed He II λ4686 nebular emission is consistent with post-asymptotic giant branch stars being the sole ionizing source in all age bins. These results limit populations of accreting WDs with photospheric temperatures ($T_{\text{eff}}$) in the range $\sim (1.5\text{−}6)$·$10^5$ K to the level at which they can account for no more than $\sim 5\text{−}10\%$ of the observed SN Ia rate. Conversely, should all WD progenitors of SN Ia go through the phase of steady nuclear burning with $T_{\text{eff}} \sim (1.5\text{−}6)$·$10^5$ K, they do not increase their mass by more than $\sim 0.03 M_\odot$ in this regime.

Key words: galaxies: ISM, elliptical and lenticular, cD – supernovae: general, white dwarfs

1 INTRODUCTION

The use of Type Ia supernovae (SNe Ia) as standard candles has been key to the discovery of the accelerating expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999). However, the nature of their progenitors remains uncertain, with increasing evidence suggesting they may arise through multiple evolutionary channels. This possible diversity, and the null detections of the progenitor of any individual SN Ia (e.g. Chomiuk 2013) has rendered population-based arguments a necessity.

The single-degenerate (SD) scenario (Whelan & Iben 1974) has long been one of the favoured progenitor channels for SNe Ia. In the classical picture, a carbon-oxygen white dwarf (WD) accretes mass from a co-orbiting binary companion, eventually exploding upon nearly reaching the critical Chandrasekhar mass ($\sim 1.4 M_\odot$). Before this happens, steady nuclear burning of the accreted material occurs on the surface of the WD over an extended period of time ($\sim 10^6$ yr) as soon as the mass transfer rate ($\dot{M}$) exceeds a few times $10^{-7} M_\odot$/yr (Nomoto et al. 2007). For lower mass transfer rates, nuclear burning occurs only in unsteady flashes, expelling matter from the WD in nova outbursts (Prialnik & Kovetz 1993). This renders it difficult...
for the WD to ever reach the Chandrasekhar mass, unless perhaps if accreting WDs undergo an extended evolutionary phase as recurrent novae binaries (Hachisu & Kato 2001). In the latter case, however, the SD scenario comes into conflict with statistics of classical/recurrent nova in the Andromeda galaxy (Soraisam & Gilfanov 2013, in preparation).

Should all SNe Ia progenitors undergo a steady nuclear-burning phase during some fraction of the time prior to explosion, their total bolometric luminosity $L_{\text{tot}}$ can easily be evaluated. It is proportional to the rate of exploding SN Ia ($\dot{N}_{\text{SNIa}}$), and to the total amount of mass $\Delta M_{\text{SB}}$ processed through steady burning, according to (Gilfanov & Bogdan 2010)

$$L_{\text{tot}} = \epsilon H \chi \Delta M_{\text{SB}} \dot{N}_{\text{SNIa}},$$

where $\epsilon H$ and $\chi$ are the energy release per unit mass of hydrogen ($\sim$6·10$^{18}$ erg/g) and the mass fraction of hydrogen ($\sim$0.72), respectively.

During steady nuclear-burning, the WD emits blackbody-like radiation with an effective temperature peaking around $T_{\text{eff}} \sim (5 - 8) \cdot 10^4$ K, making it a prodigious source of soft X-ray emission ($\sim$0.3–0.7 keV, van den Heuvel et al. 1992). Given the observed rate of SNe Ia (Totani et al. 2008; Maoz, Mannucci & Brandl 2012), there should be a large number of accreting sources at any given time according to the SD scenario, sufficient to produce an integrated soft X-ray emission that would be detectable by modern X-ray telescopes, in particular in galaxies lacking an absorbing interstellar medium. However, recent studies found very little total soft X-ray emission in gas-poor elliptical galaxies (Gilfanov & Bogdan 2010), and far too few sources (Di Stefano 2010), implying that no more than $\sim$5% of the SNe Ia in these systems formed according to the standard SD scenario.

Such a direct argument is very efficient in constraining populations of relatively high temperature white dwarfs accreting in the steady nuclear burning regime. It is, however, much less sensitive to lower temperature sources and becomes inefficient below $T_{\text{eff}} \sim 4 \cdot 10^5$ K because of interstellar absorption. These temperatures may appear if the photosphere of the WD could inflate to dimensions significantly exceeding the white dwarf radius, for example, in a so-called accretion wind state. This would shift the peak of the radiation from the soft X-ray to the extreme UV regime, with temperatures roughly around $1 - 2 \cdot 10^5$ K (Hachisu, Kato & Nomoto 1993). Although the ISM in the Milky Way would absorb such UV emission and prevent the direct detection of these SD progenitors, by the same token we can expect that hydrogen burning accreting WDs will be particular efficient ionising sources for the interstellar medium of their host galaxies.

In fact, with harder UV spectra than young O-stars, old horizontal-branch stars or post-asymptotic giant branch stars (pAGBs), the presence of a SD-progenitor population will dramatically change the character of the ionizing background of a galaxy, in particular in the absence of a central active nucleus or for regions sufficiently far from one. In turn, the hardness of the ionising background could be gauged in the presence of a diffuse ionised-gas medium, by measuring the strength of nebular emission that can only be powered by a far-UV background, e.g. the He ii recombination line at 4686 Å (He ii $\lambda$4686). The strength of this line is indeed predicted to be considerably boosted should SNe Ia originate from hot and luminous WD progenitors compared to a situation where the ionising background is dominated by old UV-bright stars (Woods & Gilfanov 2013).

Hence, in this paper, the aim is to examine whether a substantial population of steadily-accreting WDs with black-body temperatures around a few times $10^5$ K is consistent with measurements for the strength of He ii $\lambda$4686 emission from the diffuse ionised-gas of galaxies, which we will use as a gauge for the hardness of the ionising background. In particular, we focus on galaxies with >1 Gyr old passively-evolving stellar populations (also referred to as “retired galaxies”) with no sign of active galactic nuclei (AGN). Such a selection excludes the contribution of young and hot stars or of an accreting supermassive black hole to the ionising background, leaving us to consider only the presence of old UV-bright stars such as pAGB stars in addition to the possible impact of accreting WDs. Retired galaxies have been shown to often host substantial amounts of neutral gas largely confined to a disk-like planar distribution within their host galaxy (Serra et al. 2012). This neutral gas is accompanied by extended regions of lowly-ionized gas (e.g., Sarzi et al. 2006), the emission of which has long been thought to be powered by a diffuse ionizing background supplied by stellar populations (Binette et al. 1994).

Retired galaxies are therefore an ideal laboratory to check whether a substantial accreting WD population of SN Ia progenitors exists. Yet, even though the presence of such hot sources would substantially boost the observed He ii $\lambda$4686 emission from the interstellar medium of retired galaxies, the recombination lines remain intrinsically faint and their detection very challenging. For instance, in the case where pAGB stars are the only sources of He ii-ionizing photons, the strength of the He ii $\lambda$4686-line is predicted to require a signal-to-noise ($S/N$) ratio in the stellar continuum $>$500 to be detected (Woods & Gilfanov 2013). This high-quality requirement contributes not only to explain why to date there is no reported detection of He ii-emission in retired galaxies, but also sets the bar for the accuracy needed for our experiment if we wish to recognize an increase in the He ii strength due to the presence of accreting WDs.

To achieve the required data quality, we will draw from the great wealth of optical spectra of nearby galaxies available in the Sloan Digital Sky Survey (SDSS, York et al. 2000) and co-add a large number of spectra of passively evolving systems with no sign of recent star formation or AGN activity, but for which we can detect the same kind of low-ionisation nebular emission that is generally observed in nearby early-type galaxies. Such an emission is indeed always extended and has been shown to be consistent with the weak emission found in the SDSS spectra of retired galaxies, which cover most of the optical regions of these objects (Sarzi et al. 2010).

This paper is organised as follows. The data sample selection is described in Section 2. The technique used for stacking galaxy spectra and the method for estimating emission lines are described in Section 3. The derived He ii $\lambda$4686 emission is presented Section 4 and compared to modeled predictions for the SD scenario in Section 5. Concluding remarks are given in Section 6. 
Table 1. The corresponding number of galaxies left after applying each of the different sample cuts, starting from the full SDSS DR7 catalogue.

| Selection         | N     |
|-------------------|-------|
| DR7               | ~930 000 |
| Redshift cut      | ~306 000 |
| WHAN cut          | 13 875 |
| RSF cut I (PCA)   | 11 593 |
| RSF cut II (NUV-r)| 4 061  |

2 DATA SAMPLE

The sample used in this study is selected from the SDSS-II data release 7 (DR7 [Abazajian et al. 2009]). The SDSS has obtained imaging (ugriz, Fukugita et al. 1996) and spectroscopy for more than 930 000 galaxies. This was achieved with the multi-object spectrograph (Smee et al. 2012), fed with light from fibers with a fixed diameter of 3”, and wide-field CCD camera (Gunn et al. 1998) on the SDSS 2.5 m telescope (York et al. 2000; Gunn et al. 2006) at the Apache Point Observatory. Starting from the full DR7 sample we apply a number of selection criteria described below. The numbers of the samples after applying each cut are presented in Table 1.

2.1 Redshift and WHAN selection

For the stacking procedure we want to avoid galaxies for which the fixed SDSS aperture only covers the nuclear regions. Hence, we apply a lower redshift limit of $z > 0.04$, such that all spectra cover the galaxy stellar light within a diameter $>\sim 3$ kpc. We do also apply an upper redshift limit of $z < 0.1$, above which the signal-to-noise (S/N) of the SDSS spectra decreases fast. There are $\sim 306$ 000 SDSS DR7 galaxies for the adopted redshift range of $0.04 < z < 0.1$ (“Redshift cut” in Table 1).

Most critically, we want to select gas rich galaxies where the ionizing photon field is not powered by young OB-stars or accreting black holes. For this purpose we use the combination of Hα line flux and Hα/[N II]λ6584 line ratio, the so called WHAN diagram (Fernandes et al. 2011), to discriminate between objects where the nebular emission is powered by star-formation, an active galactic nucleus (AGN) or old and UV-bright stellar sources such as pAGB stars. Galaxies with detected Hα and [N II]λ6584 emission were selected from the OSSY value-added SDSS catalogue (Oh et al. 2011). In this process objects with robust emission-line fits of Hα and [N II]λ6584, i.e. with an amplitude-over-noise (A/N) ratio $> 3$ for both lines, were selected. Furthermore, objects with telluric emission contaminating these lines were excluded (Oh et al. 2011). The WHAN-diagram for the selection of galaxies with detected Hα and [N II]λ6584 lines is shown in Fig. 1. Region “SF” covers star-forming galaxies, region “AGN” galaxies hosting AGNs and region “Retired Galaxies” where old UV-bright stellar sources alone should suffice to ionize the interstellar medium (Fernandes et al. 2011). The selection-limit of the latter region is log EW$_{H\alpha} < 0.48$. We adopt a more conservative limit of log EW$_{H\alpha} = 0.3$ to minimize the AGN contamination. This selection criterium, indicated by the dashed box in Fig. 1, produces a sample of 13 875 galaxies (“WHAN cut” in Table 1).

2.2 Selecting galaxies without star formation in the last Gyr

In the last selection step, we discard galaxies hosting a significant fraction of stars younger than 1 Gyr. For this purpose we use the principal component analysis (PCA) technique of Chen et al. (2012) that is based on the work of Wild et al. (2007). The PCA method reproduces galaxy spectra by a set of orthogonal principal components. These components represent spectral features including the 4000˚A break and Balmer absorption lines that are very sensitive to the presence of young stars. Important for this work, the PCA technique of Chen et al. (2012) exploits these features to trace the fraction of stars formed in the last Gyr. After running a PCA on the individual galaxy spectra, we exclude objects where more than one per cent of the stars have formed in a recent star formation (RSF) episode in the last Gyr, resulting in a final sample of 11 593 galaxies (“RSF cut I (PCA)” in Table 1).

Complementary to the PCA technique, we separately exclude galaxies with recent star formation by combining near ultra-violet (NUV) photometry with SDSS r band magnitudes. For this purpose, we cross-match the selected SDSS sample with the galaxy evolution explorer (GALEX) database (Martin et al. 2005) to retrieve NUV magnitudes for the individual galaxies. We find available GALEX photometry for 75 per cent of the selected galaxies, i.e. for 10 406
of observed and modeled absorption line indices using a χ² minimization is given here. (2012) for details of the method, while only a brief description is provided for extinction uncertainties due to the small wave-length definitions. The reader is referred to Johansson et al. to extinction uncertainties due to the narrow wavelength definitions. The reader is referred to Johansson et al. (2012) which is based on absorption line indices. This technique was developed to break the degeneracy associated with a similar number of galaxies. The solid and dashed histograms represent the samples where galaxies with star formation in the last Gyr have been discarded using the PCA and NUV-r criteria (see text), respectively, as indicated by the labels in the upper right corner.

2.3 Stellar age estimates and age grouping

In order to better constrain the predictions concerning the strength of the He II λ4686 line within the single-degenerate progenitor model for SN Ia, we divided our final galaxy samples (“RSF cut I (PCA)“ and “RSF cut II (NUV-r)“ in Table 1) into several bins of average stellar population age. The ages are derived, together with stellar metallicity and element abundance ratios (O/Fe, Mg/Fe, C/Fe, N/Fe, Ca/Fe and Ti/Fe), using the technique from Worthey & Ottaviani (1997), and finally corrected for velocity dispersion broadening. The χ²-minimization routine adjusts the stellar population models of Lick indices from Thomas, Maraston & Johansson (2011) in order to match the observed values. This is done through a number of steps in order to carefully account for the sensitivity to the full range of element abundance ratios of the Lick indices. At each step a new set of models is used that is a perturbation of the previous best-fitting model. The best-fitting model at the final step, i.e. when the χ² is not improved by more than 1 per cent, determines the stellar population parameters of the galaxy spectrum examined.

This routine is run for all individual galaxy spectra included in the final selections (“RSF cut I (PCA)“ and “RSF cut II (NUV-r)“ in Table 1). The age distributions for the selections are shown in Fig. 3, where the solid histogram shows the distribution for the PCA selection and the dotted histogram shows the NUV-r selected analogue. The former distribution is divided in bins containing at least ~ 2000 objects, as shown by the coloured sub-histograms. The former distribution is divided in bins containing at least ~ 2000 objects, as shown by the coloured sub-histograms. This is the number needed to reach a desired S/N of ~ 500 of the stacked spectra for the detection of the He II λ4686 lines with as low predicted equivalent width values as ~ 0.05 Å, according to Woods & Gilfanov (2013), estimated using the mean S/N of the SDSS spectra of ~15. Hence, the sample is divided into four age bins (< 4 Gyr, 4 – 6 Gyr, 6 – 9

Figure 2. Left panel: NUV-r colour as a function of absolute r band magnitude M(r) for the 10 406 WHAN selected galaxies with available GALEX NUV magnitudes. The dashed line represents the limit from Kaviraj (2007), for which galaxies falling in the region below have experienced star formation in the last Gyr. Right panel: Distribution of NUV-r colours for the same sample selection as above.

Figure 3. Distribution for the luminosity-weighted mean stellar age of our selected sample of retired galaxies. The coloured sub-histograms represent our four adopted age bins, which contain a similar number of galaxies. The solid and dashed histograms represent the samples where galaxies with star formation in the last Gyr have been discarded using the PCA and NUV-r criteria (see text), respectively, as indicated by the labels in the upper right corner.
Table 2. Salient features of each of the co-added spectra analysed in this work. The columns give the age range of the galaxies in each group (col. 1), method for discarding galaxies with stars formed in the last Gyr (col. 2), number of spectra in each group (col. 3) and resulting S/N for the stacked spectra (col. 4).

| Stack | N       | S/N  |
|-------|---------|------|
| All ages | PCA     | 11593 | 1751 |
| <4 Gyr | PCA     | 2740  | 882  |
| 4-6 Gyr | PCA     | 3380  | 1044 |
| 6-9 Gyr | PCA     | 2729  | 1000 |
| >9 Gyr | PCA     | 2744  | 1018 |
| <6 Gyr | NUV-r   | 1953  | 829  |
| >6 Gyr | NUV-r   | 2108  | 951  |

Gyr and > 9 Gyr), each with a number of objects greater than 2000. These numbers are presented in Table 2 for each age bin together with the resulting S/N after stacking all individual spectra (see Section 3.1). The more conservative age bin with the resulting S/N after stacking all galaxies in each bin.

3 CO-ADDITION AND ANALYSIS OF THE RESULTING STACKED SPECTRA

3.1 Stacking technique

Prior to stacking the spectra of the different sample selections, a few corrections are applied to the individual spectra:

(i) The additional flux calibration of Yan (2011) is applied to correct for small-scale fluctuations.

(ii) The spectra are de-reddened for Galactic extinction following the extinction curve of diffuse gas from O’Donnell (1994) for an $E(B-V)$ value of 3.1, and using the Galactic E(B–V) values from the maps of Schlegel, Finkbeiner & Davis (1998).

(iii) The spectra are brought to rest-frame wavelengths and to a common wavelength grid.

After applying these corrections, the spectra of each sample selection are co-added to produce high S/N stacked spectra. During the stacking process, the statistical error arrays associated with each SDSS spectrum are co-added in quadrature. The mean S/N around 5000 Å is estimated to be 1750 for stacking all galaxies selected with the PCA criterion (see Section 2.2).

It should be noted that redshift uncertainties have not been accounted for in the stacking process. Instead, we have verified, through Monte Carlo simulations, that including these uncertainties, the flux density errors of the stacked spectra increase by ~10 per cent only.

3.2 Emission line fitting

With the aim of measuring emission lines we adopt the fitting code GANDALF (Sarzi et al. 2006). A brief description of this code is given here, while the reader is referred to Sarzi et al. (2006) for a detailed description. The goal of GANDALF is the separation of emission and absorption spectra of composite galaxy spectra. In the first step, the emission lines of the wavelength range under consideration are masked and the PPF code (Cappellari & Emsellem 2004) is used for measuring kinematic broadening of the absorption spectrum with a set of best-fitting stellar templates. The emission line mask is then lifted and with the stellar kinematics fixed, GANDALF reassesses the stellar continuum by simultaneously fitting a number of Gaussian emission line templates consisting of both recombination and forbidden lines.

As stellar templates we adopt the full medium-resolution Isaac Newton telescope library (MILES, Sánchez-Blázquez et al. 2006). This library consists of observed spectra for 985 solar neighborhood stars. This is the stellar library with the largest parameter coverage in the literature and, hence, allows us to achieve a very precise fit to the stellar continuum of the stacked spectra. The precision of the fit is significantly higher compared to using stellar population models as templates (Cappellari et al. 2007; Sarzi et al. 2010).

The MILES library has a fixed instrumental full width half maximum (FWHM) resolution $\Delta \lambda \sim 2.5$ Å (Beifiori et al. 2011), while the SDSS resolution is fixed at $R \sim 2000$ which corresponds to a FWHM $\Delta \lambda \sim 5$ Å at 5000 Å. Even though the resolutions are close, the MILES resolution is slightly higher at wavelengths longer than 5000 Å and vice versa. Hence, we degrade both the SDSS and MILES spectra to match each other prior to running GANDALF.

We perform our GANDALF fitting in the wavelength window between 3800 Å and 6800 Å, which includes many prominent absorption features useful for constraining the best-fitting set of stellar templates, as well as a wide range of important emission lines. This wavelength range specifically covers the strong Hα and [N II] $\lambda 6584$ lines, which are useful for constraining the position and Gaussian width of weaker emission lines such as He II $\lambda 4686$ and Hβ. In partic-
Figure 5. Data and model of stacked spectrum. Upper panel: total spectrum obtained by co-adding the spectra of all galaxies in our sample of quiescent objects (11593 galaxies) and selected using the PCA criterium (see Section 2), together with our best-fitting model (red line). The stellar component of this model is shown by the dashed red line, whereas our best-fitting nebular spectrum is shown in blue. Lower panel: difference between the stacked spectrum and best-fitting stellar model around the position of the He\textsc{ii} $\lambda$4686 line (black solid line), together with our best-fitting emission-line model (blue line). The dashed horizontal line shows the level of noise in the residuals (standard deviation) of the overall fit to the data in a wavelength region $\pm$200 Å around 4686 Å. In the 4600-4800 Å wavelength range, beside He\textsc{ii} $\lambda$4686, we also fit for the [ArIV] lines at 4711 and 4740 Å. The position of all lines is indicated by dotted vertical lines, with labels for their name. In this case, the ratio between the Gaussian model amplitude and the level of noise in the residuals, $A/N$, which relates to the detection level of the lines, is 2.8 for the He\textsc{ii} $\lambda$4686-line.

As already mentioned, for the adopted wavelength range we fit a large number of emission lines. However, in this paper we focus on the detection of the He\textsc{ii} $\lambda$4686 line. In addition to this line, we will also use the results for H$\beta$ and [O\textsc{iii}] $\lambda$5007 (see Section 5) in order to constrain the ionization state of the gas. All other detected optical lines will be discussed in a companion paper (Johansson et al. in prep.).
Table 3. Age range and selection criterium of the galaxies in each group (col. 1-2), cols. 3-5 list the A/N ratio corresponding to our fit for the \( \text{He} \, \lambda 4686, \, \text{H} \beta \) and \([\text{O} \, \text{III}] \lambda 5007\) lines, respectively, whereas cols. 6 and 7 list the values for the \( \text{He} \, \lambda 4686/\text{H} \beta \) and \([\text{O} \, \text{III}] \lambda 5007/\text{H} \beta \) line ratios. Col. 8 gives the derived average stellar population age.

| Stack | \( \text{He} \, \lambda 4686 \) | \( \text{H} \beta \) | \([\text{O} \, \text{III}] \lambda 5007 \) | \( \text{He} \, \lambda 4686/\text{H} \beta \) | \([\text{O} \, \text{III}] \lambda 5007/\text{H} \beta \) | Age (Gyr) |
|-------|-------------------|----------|-----------------|-----------------|-----------------|--------|
| All   | PCA               | 2.8      | 32.2            | 53.4            | 0.073±0.021     | 2.24±0.06 | 4.7    |
| <4 Gyr| PCA               | 2.7      | 32.6            | 51.9            | 0.075±0.023     | 1.95±0.06 | 2.8    |
| 4-6 Gyr| PCA               | 3.0      | 30.9            | 53.6            | 0.089±0.023     | 2.22±0.07 | 4.9    |
| 6-9 Gyr| PCA               | 2.6      | 28.0            | 47.8            | 0.087±0.026     | 2.31±0.08 | 6.6    |
| >9 Gyr| PCA               | 2.6      | 23.8            | 39.9            | 0.103±0.029     | 2.32±0.09 | 10.7   |
| <6 Gyr| NUV-\(r\)         | 2.7      | 28.5            | 52.4            | 0.088±0.023     | 2.28±0.07 | 3.0    |
| >6 Gyr| NUV-\(r\)         | 2.6      | 23.8            | 40.1            | 0.101±0.026     | 2.31±0.09 | 8.7    |

4 STACKING RESULTS

In this section, we present the results for the lines \( \text{He} \, \lambda 4686, \, \text{H} \beta \) and \([\text{O} \, \text{III}] \lambda 5007\) from the SED fitting of the stacked spectra using \texttt{GANDALF}. In particular, we assess the confidence level of the detection of the weak \( \text{He} \, \lambda 4686\) line. Furthermore, we derive the average stellar population age of the emission corrected stacked spectra.

4.1 Emission lines

The spectrum obtained when stacking all selected galaxies using the PCA criterium (see Section 2.2) is presented in Fig. 5 (upper panel) together with our best-fitting model. The stacked spectrum is matched by the best-fit template to a very high precision and a range of prominent emission lines are apparent. Corresponding figures for the rest of the stacked spectra are presented in Appendix A. The lower panel of Fig. 5 shows the difference between the stacked spectrum and best-fitting stellar template, together with the best-fitting emission-line model around the position of \( \text{He} \, \lambda 4686\). A positive feature is clearly visible at the location of the \( \text{He} \, \lambda 4686 \) line, which is well matched while adopting the same Gaussian profile as used when fitting the much stronger \([\text{N} \, \text{II}] \lambda 6548, \lambda 6584\) emission at 6584 Å. Most of the other features in the residuals of our stellar fit can be explained in light of the limitations of our adopted stellar templates (see Section 3.2). For instance, the strong negative feature at 4668 Å corresponds to a \( C_2\)-absorption feature, which is not perfectly matched by the stellar model because the templates cannot account for the super-solar Carbon abundance that is observed in massive galaxies (Johansson et al. 2012).

Table 3 lists the A/N values for the derived \( \text{He} \, \lambda 4686, \, \text{H} \beta \) and \([\text{O} \, \text{III}] \lambda 5007\) lines (cols. 3-5) for each stacked spectrum. In the comparison with modeled emission line predictions for the SD scenario we focus on emission line ratios instead of individual line fluxes (see Section 5). Hence, the value of the \( \text{He} \, \lambda 4686/\text{H} \beta \) flux ratio is presented in Table 3 (col. 6), together with the \([\text{O} \, \text{III}] \lambda 5007/\text{H} \beta \) line ratio (col. 7) used for constraining the ionization parameter (see Section 3). The strong \([\text{O} \, \text{III}] \lambda 5007 \) and \( \text{H} \beta \) lines are always undoubtedly detected with A/N ratios greater than 40 and 23, respectively. The A/N ratios of the \( \text{He} \, \lambda 4686 \) line instead falls in the range 2.6-3.0. As mentioned above, the residual noise determining the A/N value of this weak line is dominated by systematics, i.e. the ability of the stellar templates to recover the stacked absorption spectra. Thus, in the following section we assess the confidence level of the detection of the \( \text{He} \, \lambda 4686\) line. At this point, we note that for all age bins we appear to find consistently low values (less than 0.1) for the \( \text{He} \, \lambda 4686/\text{H} \beta \) ratio. We also note that the \( \text{He} \, \lambda 4686 \) flux appears to be slightly overestimated in the oldest age bin (see Appendix A for more details).

4.2 The A/N ratio as a tracer for the detection level of \( \text{He} \, \lambda 4686\)

To further understand the connection between any measured value of the A/N ratio and the level of detection for the \( \text{He} \, \lambda 4686\) line, we have used the \texttt{GANDALF} procedure to look for emission lines with the same line profile of the strong \([\text{N} \, \text{II}] \lambda 6548, \lambda 6584\) lines in spectral regions where no significant emission is known to exist. More specifically, by repeating this experiment 100 times at random spectral positions around the \( \text{He} \, \lambda 4686 \) line (±200 Å) we have assessed the probability of measuring any given A/N value
just by chance with our fitting procedure. In fact, assuming that the fit to the stellar spectrum is not particularly worse around the position of the He II λ4686 line than right on it, this test implicitly accounts for spurious emission-line measurements (and corresponding A/N values) that would be due to our limited ability to fit the real stellar spectra of galaxies with our current set of stellar templates, resulting in GANDALF attempting to compensate for this problem by means of a Gaussian feature. The cumulative distribution for the fraction of A/N values returned by our fake emission-line fits during this test is shown in Fig. 6. The plotted distribution was derived from the stacked spectrum corresponding to our entire sample using the PCA criterium (see Section 2.2), and similar distributions are obtained also from the stacked spectra for each of our stellar-age subsamples. This is not surprising as all spectra are characterized by similar systematic patterns of residuals around 4686 Å (compare Fig. 5 with Fig. A1–A6). In the H β versus [MgFe]' line-strength diagram (Thomas et al. 2003) the distribution plotted in Fig. 6 indicates that there is less than 5% probability of finding an A/N 2.0 or above, and less than 1% probability for values equal or in excess of an A/N 2.4.

The values of the A/N ratio for the derived He II λ4686 lines always fall in the range between 2.6 and 3.0 (Table 3). Given that there is less than 1% probability of measuring A/N values of 2.4 and above for the He II λ4686 line in our stacked spectra, this line is robustly detected for all groups of galaxies with different luminosity-weighted stellar ages.

### 4.3 Stellar population ages

By subtracting the emission line spectra from the stacked galaxy spectra, we get clean absorption spectra for which we derive the Lick indices (see Section 2.3). Fig. 7 shows the classic H β versus [MgFe]' line-strength diagram (Thomas et al. 2003) for the Lick indices derived on the stacked spectra, and with the TMJ models overlaid with ages and metallicities as given by the labels. This diagram is useful for visualizing stellar population parameters and the trend of the stacked spectra clearly follows that of the selected age bins. Furthermore, we apply our method for deriving stellar population parameters from observed Lick indices (Johansson et al. 2012), see Section 2.3, and the derived ages for each of the stacks are presented in Table 3 (col. 8). These measurements confirm that the division into age bins, based on the individual spectra, was successful.

At this point, we note that even though we have excluded objects with significant fractions of stars younger than 1 Gyr, our luminosity-weighted ages could still be biased to lower values owing to the possible presence of a small fraction of ~1 to 2-Gyr-old populations that would still be significantly brighter than the remaining older bulk of the stellar population. This is important to keep in mind when trying to constrain the role of accreting white dwarfs as progenitors of SN Ia, since the rate of SN Ia per unit mass decreases fast as a function of stellar age, e.g., a 1-Gyr-old stellar population will produce over an order of magnitude more SN Ia than a 10-Gyr-old population (Tutani et al. 2008; Maoz et al. 2012).

To account for this possibility in the analysis of the next section, we perform the following simulations. We compute the luminosity-weighted age of a composite stellar population consisting of the mass fractions $f_m$ of a 1 Gyr old SSP and $1 - f_m$ of a 10 Gyr old SSP. The composite stellar populations were modeled using the spectra of SSP models from Bruzual & Charlot (2003) and the luminosity weighted ages were derived using absorption line indices as described in Section 2.3.
old components, respectively. The luminosity-weighted ages of the composite populations are determined from absorption line indices as described in Section 2.3. The resulting dependence of the luminosity-weighted age on the mass fraction \( f_m \) of the 1 Gyr old SSP is shown in Fig. 8. For instance, a 5% mass fraction of 1-Gyr-old stars combined with a 95% mass fraction of 10-Gyr-old stars will result in a luminosity-weighted age of \( \sim 4 \) Gyr. The obtained dependence will be used in the next section to derive predictions for the SD scenario for the different composite populations to estimate the range of possible strengths of the He II line at a given stellar population age.

5 CONSTRAINTS ON THE SD SCENARIO

We now compare our emission-line results with the modeled predictions from [Woods & Gilliland (2013)] for the photoionisation of the interstellar medium that include possible SD progenitors of SN Ia. In particular, we focus on predicted values of the He II \( \lambda 4686/\lambda 5007 \) line ratio. This quantity remains as sensitive to the hardness of ionizing radiation as the He II \( \lambda 4686 \) line itself, but does not depend on assumptions regarding dust extinction or the fraction of ionizing photons that is intercepted by the interstellar medium. It does depend on the rate of ionizing photons incident on the gas (per Hydrogen atom, the so-called ionization-parameter \( U \)). This is constrained by the observed \( \Delta M_{SB} = 0.3 \, M_\odot \), a WD effective temperature of \( T_{\text{eff}} = 2 \cdot 10^5 \) K and the age dependent SN Ia rate as given by the delay time distribution of [Totani et al. (2008)]. To illustrate the impact of non-SSP stellar populations, the dashed black line shows the predictions for composite stellar populations combining 1 and 10 Gyr old SSPs (see text for details). Both single-age and two-burst models predict declining He II \( \lambda 4686/\lambda 5007 \) values, reflecting the cosmic decrease in the SN Ia rate. The observed values for the He II \( \lambda 4686/\lambda 5007 \) ratio are well below these models, appearing instead consistent with pAGBs being the only, or at least dominant, source of ionizing photons for the diffuse gas of quiescent galaxies.

![Figure 9. Comparison between observed values (filled squares, presented in Table 3) of the He II \( \lambda 4686/\lambda 5007 \) line ratio and our model predictions as a function of stellar age. The vertical and horizontal error-bars attached to our measurements represent the 1\( \sigma \)-errors on the line ratio and the range of stellar ages encompassed by each of our subsamples, respectively. The red and blue thick lines show the predictions for ionization by single type of ionizing sources, either by pAGB stars or by accreting WDs in the SD scenario for SN Ia progenitors, respectively. The black solid line shows the predicted values for the He II \( \lambda 4686/\lambda 5007 \) ratio when both components are considered. In this case the spectrum of the stellar component (dominated by pAGB starts) was computed using the SSP models from Bruzual & Charlot (2003), whereas the luminosity of the SD SN Ia progenitors was computed using Eq. 1. In the latter, we assumed \( \Delta M_{SB} = 0.3 \, M_\odot \), a WD effective temperature of \( T_{\text{eff}} = 2 \cdot 10^5 \) K and the age dependent SN Ia rate as given by the delay time distribution of [Totani et al. (2008)]. To illustrate the impact of non-SSP stellar populations, the dashed black line shows the predictions for composite stellar populations combining 1 and 10 Gyr old SSPs (see text for details). Both single-age and two-burst models predict declining He II \( \lambda 4686/\lambda 5007 \) values, reflecting the cosmic decrease in the SN Ia rate. The observed values for the He II \( \lambda 4686/\lambda 5007 \) ratio are well below these models, appearing instead consistent with pAGBs being the only, or at least dominant, source of ionizing photons for the diffuse gas of quiescent galaxies.](figure.png)
fraction of 1-Gyr-old stars in the composite models brings an overall higher rate of SN Ia and hence larger values of the predicted He II $\lambda 4686$/H$\beta$ ratio than in the case of a pure old stellar population, whereas the converse holds for lower values of the luminosity-weighted age. The predictions shown in Fig. 10 for the single-age case and our particular composite models thus represent conservative upper and lower boundaries for the He II $\lambda 4686$/H$\beta$ ratio that should bracket the case of less extreme, and more plausible, star-formation histories. The observed ratios are clearly well below those expected from models including a large population of accreting WDs. Notably, they are in agreement (within 1σ) with pAGB stars being the sole ionizing source in retired galaxies. In Fig. 9 we only present the observed values for the PCA selection (see Section 2.2), which are in good agreement with the observed values for the NUV-r selection (see Table 3).

Assuming that all WD progenitors of SN Ia go through a steady nuclear-burning phase, we can constrain the maximum amount of mass accreted at any photospheric temperatures above $\sim 10^5$ K by requiring that our models do not conflict with the observed He II $\lambda 4686$/H$\beta$-ratio. This is shown in Fig. 10 (left axis) as a function of $T_{\text{eff}}$.

Note that in the wind models of Hachisu et al. (1999), photospheric temperatures below $10^5$ K require mass accretion rates in excess of $10^{-5}$ $M_\odot$/yr, which would result in a prohibitively high mass loss rate and low mass accumulation efficiency for SN Ia progenitors. They are therefore irrelevant in the context of SN Ia progenitors in retired galaxies, because of the mass conservation considerations.

1 Note that derived for the mean age ($\approx 3$ Gyr, see Table 3) and observed He II $\lambda 4686$/H$\beta$-ratio of the youngest age-bin (<4 Gyr) where the SN Ia rate is high. This is derived accounting for the contribution from pAGBs. Taking the observed He II $\lambda 4686$/H$\beta$-ratio at face value, it may be concluded that the maximum mass accreted by a typical white dwarf – successful SN Ia progenitor – at photospheric temperatures of $(1 - 7) \times 10^5$ K lies in the range $\sim (1 - 4) \times 10^{-3}$ $M_\odot$. Note that the upper end of the temperature range is in fact more tightly constrained by X-ray observations (Gilfanov & Bogdan 2010). Accounting for the statistical errors on the He II $\lambda 4686$/H$\beta$-ratio at the 90% confidence level, we obtain an upper limit of $\sim 0.04$ $M_\odot$, also falling far short of the minimum $0.3M_\odot$ required to trigger a SN Ia explosion.

Alternatively, we can estimate the maximum fraction of SN Ia originating from the SD-channel, again assuming that a white dwarf needs to accrete at least $\Delta M_{\text{SB, min}} = 0.3$ $M_\odot$ in order to produce a supernova. This fraction is shown on the right-hand axis of Fig. 10 and does not exceed $\sim 0.01$ for the observed He II $\lambda 4686$/H$\beta$-ratio. Accounting for the errors at the 90% confidence level, we find an upper limit on the maximum fraction of SN Ia originating from the SD-channel of $< 0.1$. Note that the typical value of $\Delta M_{\text{SB}}$ in the SD scenario should be larger than the assumed $\Delta M_{\text{SB, min}} = 0.3$ $M_\odot$ resulting in an even more constraining upper limit.

6 CONCLUSIONS

We study nebular emission in passively evolving (“retired”) galaxies to constrain their populations of hot accreting WDs.
new context of the SD scenario of SNe Ia. In the SD scenario, a WD accretes hydrog-en-rich material from a companion star until sufficient mass has accumulated to trig-ger a thermonuclear explosion. During the accretion phase, the WD emits UV radia-tion and the collective emission from a population of such objects will alter the ionization balance in the warm/cold component of the interstellar medium in re-tired galaxies where mainly pAGB stars are expected (weak) ionizing sources. Hence, the population of accreting WDs can be constrained by the strength of He ii recombination lines.

For this purpose, we select galaxies from the SDSS with detected emission lines and where the ionizing background is not powered by young stars in star forming regions or AGNs. Furthermore, we select galaxies with stellar popu-lation ages > 1Gyr that have not experienced star formation episodes in the last Gyr. In total we select ~ 11500 galaxies and their spectra are co-added in four bins of stellar population age resulting in ~ 2000 galaxies in each bin, producing high quality stacked spectra with S/N values exceeding 800. For each stacked spectrum, we fit the SED in a wide wavelength range, 3800-6800 Å, where a number of emission lines reside including He ii λ4686, using the code GANDALF (Sarzi et al. 2006) and the observed stellar library MILES (Sánchez-Blázquez et al. 2006) as templates for the stellar continuum. In the fitting process, the kinematics and position of He ii λ4686 are constrained by the strong [N ii] λ6548/6584 line doublet.

We extensively test the detection level of emission lines in the wavelength region around 4686 Å and conclude that we, for the first time, detect the He ii λ4686 line in retired galaxies. The line strengths of the stacked spectra in the four age bins are compared to the photoionization models from Woods & Gilfanov (2013) that include the ionizing contribution of accreting WDs in the SD scenario. For this comparison we focus on the He ii λ4686/Hβ line ratio, which is insensitive to dust reddening and the covering fraction of gas. We find that in all age bins the He ii λ4686/Hβ ratio is (much) smaller than that expected in the SD scenario. For galaxies in the youngest age bin (1Gyr < t_{galaxy} < 4 Gyr), where the SN Ia rate is the highest for the consid-ered range of stellar ages, the He ii λ4686 line is more than 10 times weaker than predicted by the SD scenario. On the other hand, the strength of the nebular He ii λ4686 emission is consistent with pAGB stars being the sole ionizing source in all age bins.

These results exclude the presence of any significant population of accreting WDs with photospheric temperatures in the ~ (1.5 - 7) · 10^4 K range. Thus, only a small fraction of less than ~ 5 - 10% of SN Ia observed in retired galaxies could originate according to the classical version of the SD scenario. Furthermore, irrespectively of the partic-u-lar scenario, should all WD progenitors of SN Ia go through the phase of steady nuclear burning with the photospheric temperature range ~ (1.5 - 7) · 10^4 K, they do not increase their mass by more than a few times 10^{-2} M_☉ in this regime.

In this paper we have mainly focused on the He ii λ4686 line, although we detect a large number of optical emission lines in the stacked spectra. A general discussion of observed optical lines in retired galaxies, as well as the inferred properties of the associated dust, will be presented in a subse-quent paper (Johansson et al. in prep.).

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Figure A1. Data and model of stacked spectrum. Upper panel: total spectrum obtained by co-adding the spectra of all galaxies in our sample with luminosity-weighted mean stellar ages <4 Gyr (2740 objects) and selected using the PCA criterium (see Section 2), together with our best-fitting model (red line). The stellar component of this model is shown by the dashed red line, whereas our best-fitting nebular spectrum is shown in blue. Lower panel: difference between the stacked spectrum and best-fitting stellar model around the position of the He\textsc{ii} $\lambda$4686 line (black solid line), together with our best-fitting emission-line model (blue line). The dashed horizontal line shows the level of noise in the residuals (standard deviation) of the overall fit to the data in a wavelength region \(\pm 200\ \text{Å} \) around 4686 Å. In the 4600-4800 Å wavelength range, beside He\textsc{ii} $\lambda$4686, we also fit for the [Ar\textsc{iv}] lines at 4711 and 4740 Å. The position of all lines is indicated by dotted vertical lines, with labels for their name. In this case, the ratio between the Gaussian model amplitude and the level of noise in the residuals, $A/N$, which relates to the detection level of the lines, is 2.7 for the He\textsc{ii} $\lambda$4686-line.

APPENDIX A: FITS FOR ALL SPECTRA

Figs. A1-A6 show the stacked spectra for our age bins, together with their corresponding best-fitting stellar model. Overall, we obtain very satisfactory fits also for the stacked spectra of the subsamples. Furthermore, we nearly always find in the residuals between the data and the stellar model a clear Gaussian feature at the expected position of the He\textsc{ii} $\lambda$4686 line, which can be well matched using the same best-fitting line profile as that of the strong [N\textsc{ii}] $\lambda$6548,6584 lines. Only for the stacked spectrum corresponding to our oldest age bins (Fig. A4 and A6), we find a less regular and somewhat broader positive feature in the residuals between the data and stellar model. Hence, the estimated He\textsc{ii} $\lambda$4686 line flux of the oldest age bin should probably be regarded as an upper limit.

The values of the $A/N$ ratio for the He\textsc{ii} $\lambda$4686 lines always fall in the range between 2.6 and 3.0 (see Table 3). Given that there is less than 1% probability of measuring $A/N$ values around 2.4 or above just by chance in the wavelength region around the He\textsc{ii} $\lambda$4686 line (see Section 4.2), this line is robustly detected also in the stacked spectra for the groups of galaxies with different luminosity-weighted stellar ages.
Figure A2. Same as Fig. 5 in the main manuscript and Fig. A1 but for the spectrum obtained by co-adding the spectra of all galaxies in our sample with luminosity-weighted mean stellar ages between 4 and 6 Gyr (3380 objects) and selected using the PCA criterion (see Section 2). The fit to the He II $\lambda 4686$ line has an $A/N=3.0$.

Figure A3. Same as Fig. 5 in the main manuscript and Figs. A1-A2 but for the spectrum obtained by co-adding the spectra of all galaxies in our sample with luminosity-weighted mean stellar ages between 6 and 9 Gyr (2729 objects) and selected using the PCA criterion (see Section 2). The fit to the He II $\lambda 4686$ line has an $A/N=2.6$. 
Figure A4. Same as Fig. 5 in the main manuscript and Figs. A1-A3 but for the spectrum obtained by co-adding the spectra of all galaxies in our sample with luminosity-weighted mean stellar ages $>9$ Gyr (2744 objects) and selected using the PCA criterium (see Section 2). The fit to the He ii $\lambda 4686$ line has an $\lambda/N=2.6$.

Figure A5. Same as Fig. 5 in the main manuscript and Figs. A1-A4 but for the spectrum obtained by co-adding the spectra of all galaxies in our sample with luminosity-weighted mean stellar ages $<6$ Gyr (1953 objects) and selected using the NUV-r criterium (see Section 2). The fit to the He ii $\lambda 4686$ line has an $\lambda/N=2.7$. 
Figure A6. Same as Fig. 5 in the main manuscript and Figs. A1-A5 but for the spectrum obtained by co-adding the spectra of all galaxies in our sample with luminosity-weighted mean stellar ages $>6$ Gyr (2108 objects) and selected using the NUV-r criterium (see Section 2). The fit to the He $\text{II} \lambda 4686$ line has an $A/N=2.6$. 