The detection of [Ne v] emission in five blue compact dwarf galaxies

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ABSTRACT

We report the discovery of the high-ionization [Ne v] λ3426 Å emission line in the spectra of five blue compact dwarf (BCD) galaxies. Adding the three previously known BCDs with [Ne v] emission, the entire sample of such galaxies now contains eight objects. The detection of this line implies the presence of intense hard ionizing radiation. Such radiation cannot be reproduced by models of high-mass X-ray binaries or massive stellar populations. Other mechanisms, such as active galactic nucleus (AGN) and/or fast radiative shocks, are needed. We consider that fast radiative shocks are the most likely mechanism. The observed [Ne v] λ3426/He ii λ4686 flux ratios in all eight galaxies can be reproduced by radiative shock models with shock velocities in the ~300–500 km s⁻¹ range, and with the shock ionizing contribution being ~10 per cent of the stellar ionizing contribution. However, we cannot rule out that this 10 per cent part is produced by an AGN rather than by radiative shocks.

Key words: ISM: abundances – H II regions – galaxies: abundances – galaxies: evolution – galaxies: formation – galaxies: irregular – galaxies: ISM.

1 INTRODUCTION

Blue compact dwarf (BCD) galaxies are actively star forming dwarf galaxies in the local Universe. They have a heavy element mass fraction Z in the range 1/30–1/2 Z⊙ (e.g. Izotov & Thuan 1999), assuming a solar oxygen abundance 12 + log (O/H) = 8.69 (Asplund et al. 2009). Thus, BCD massive stellar populations have properties intermediate between those of massive stars in solar-metallicity galaxies and those of the first stars. The hardness of the ionizing radiation in BCDs has long been known to increase with decreasing metallicity (e.g. Campbell, Terlevich & Melnick 1986). BCDs then constitute excellent nearby laboratories for studying high-ionization emission in a very metal deficient environment.

The presence of hard radiation in BCDs is supported by the fact that strong nebular He ii λ4686 emission is often seen in their spectra, with a flux that increases with decreasing metallicity of the ionized gas (Guseva, Izotov & Thuan 2000; Thuan & Izotov 2005). Besides He ii emission, high-ionization emission lines of heavy elements ions are also seen in the spectra of some BCDs. Fricke et al. (2001) and Izotov, Chaffee & Schaerer (2001) first detected the high-ionization [Fe v] λ4227 emission line in the BCDs Tol 1214–277 and SBS 0335–052E, respectively. The presence of this line, just as that of the He ii λ4686 line, requires ionizing radiation with photon energies in excess of 4 ryd (54.4 eV) if ionized by radiation. Izotov et al. (2001) discovered [Fe v]–[Fe vii] emission in SBS 0335–052E, implying that this BCD contains intense hard radiation, given that the ionization potential of Fe⁶⁺ is 5.5 ryd and that of Fe⁷⁺ is 7.3 ryd. Later, Izotov et al. (2004a) and Thuan & Izotov (2005) discovered [Ne v] λ3426 emission in the three BCDs Tol 1214–277, SBS 0335–052E and HS 0837+4717. This line is often seen in Seyfert 2 galaxies, powered by the hard non-thermal radiation of an active galactic nucleus (AGN). Furthermore, Genzel et al. (1998) and Armus et al. (2007) have also detected the mid-infrared (MIR) [Ne v] λ14.3 μm and λ24.3 μm emission lines in several massive galaxies, and have attributed them also to the presence of an AGN. On other hand, no MIR [Ne v] emission line has ever been detected in a BCD. In particular, all the three above BCDs with a detected [Ne v] λ3426 emission line were observed with ISO and Spitzer (Thuan et al. 1999; Houck et al. 2004; Wu et al. 2006; Hunt et al. 2010), but no MIR [Ne v] emission line was seen, probably because of the faintness of the lines and the insufficient sensitivity of the ISO and Spitzer space observatories. The existence of the [Ne v] λ3426 emission line requires the presence of hard radiation with photon energies above 7.1 ryd, that is, in the extreme-ultraviolet (extreme-UV) and soft X-ray range. Such hard ionizing radiation is confirmed by the detection of [Ne iv] (the ionization potential of Ne³⁺ is 4.7 ryd) and [Fe v]–[Fe viii] emission in Tol 1214–277 (Izotov et al. 2004b).

While the presence of hard radiation is well established in some BCDs, the origin of this radiation is much less clear, in spite of...
Table 1. General characteristics of galaxies.

| Name     | RA (J2000.0) | Dec. (J2000.0) | g (mag) | Mg (mag) |
|----------|--------------|---------------|---------|----------|
| J0905+0335 | 09:03:51.09 | +03:35:30.38 | 17.6 | -18.4 |
| J0920+5234 | 09:20:56.08 | +52:34:04.32 | 15.7 | -16.8 |
| J1016+3754 | 10:16:24.53 | +37:54:49.97 | 15.9 | -15.1 |
| J1044+0553 | 10:44:57.80 | +03:53:13.15 | 17.5 | -16.0 |
| J1050+1538 | 10:50:32.51 | +15:38:06.31 | 18.2 | -19.4 |
| J1053+5016 | 10:53:10.82 | +50:16:35.21 | 19.9 | -11.4 |
| J1230+1202 | 12:30:48.60 | +12:02:42.82 | 16.7 | -14.4 |
| J1323-0132 | 13:23:47.47 | -01:32:51.95 | 18.1 | -16.7 |
| J1423+2257 | 14:23:42.88 | +22:57:28.79 | 17.9 | -17.7 |
| J1426+3822 | 14:26:38.22 | +38:22:58.67 | 18.2 | -16.6 |
| J1448-0110 | 14:48:05.36 | -01:10:57.71 | 16.4 | -18.8 |
| J1545+0858 | 15:45:43.55 | +08:58:01.35 | 16.9 | -19.0 |


We have obtained new high signal-to-noise ratio spectrophotometric observations for 12 BCDs with the 6.5-m MMT on the nights of 2010 April 13 and 2011 March 4–5. In constructing the observational sample, we have selected from the SDSS DR7 high-excitation spectra in the blue wavelength region of a sample of BCDs with δHe II 4686 emission, that is, those with I(He II 4686)/I(Hβ) ≥ 1–2 per cent. This selection criterion is motivated by the fact that the [Ne v] emission in Tol 1214—277, SBS 0335—052E and HS 0837+4717 is associated with relatively strong He II emission. The general characteristics of 12 BCDs are listed in Table 1 in the order of increasing right ascension. All observations were made with the Blue Channel of the MMT spectrograph. We used a 1.5 × 180 arcsec2 slit and a 800 grooves mm−1 grating in first order. The above instrumental setup gave a spatial scale along the slit of 0.6 arcsec pixel−1, a scale perpendicular to the slit of 0.75 Å pixel−1, a spectral range of 3200–5200 Å and a spectral resolution of 3 Å (full width at half-maximum, hereafter FWHM). The seeing was ~1 arcsec during both runs. The total exposure times varied between 45 and 60 min. Each exposure was broken up into three to four subexposures, not exceeding 15 min each, to allow for the removal of cosmic rays. Three Kitt Peak IRS spectroscopic standard stars, G191B2B, Feige 34 and HZ 44, were observed at the beginning, middle and end of each night for flux calibration. Spectra of He + Ar comparison arcs were obtained before or after each observation to calibrate the wavelength scale.

The two-dimensional spectra were bias-subtracted and flat-field-corrected using IRAF. We then used the IRAF software routines IDENTIFY, REIDENTIFY, FITCOORD and TRANSFORM to perform wavelength calibration and correct for distortion and tilt for each frame. Night sky subtraction was performed using the routine BACKGROUND. The level of night sky emission was determined from the closest regions to the galaxy that are free of galactic stellar and nebular line emission, as well as of emission from foreground and background sources. Then, the two-dimensional spectra were flux-calibrated using observations of standard stars. One-dimensional spectra were finally extracted from each two-dimensional frame using the APALL routine. The emission-line fluxes were measured using the IRAF SPLIT routine. The line flux errors listed include statistical errors derived with SPLOT from non-flux calibrated spectra, in addition to errors introduced in the standard star absolute flux calibration. Since the differences between the response curves derived for the three standard stars are not greater than 1 per cent, we set the errors in flux calibration to 1 per cent of the line fluxes. The line flux errors will be later propagated into the calculation of abundance errors. The line fluxes were corrected for both reddening (Whitford 1958) and underlying hydrogen stellar absorption derived simultaneously by an iterative procedure as described in Izotov, Thuan & Lipovetsky (1994). The extinction coefficient C(Hβ) for the line flux correction for interstellar dust is derived from the observed decrement of the Balmer hydrogen emission lines.

The corrected line fluxes 100 × I(λ)/I(Hβ), extinction coefficients C(Hβ), equivalent width of the Hβ emission line [EW(Hβ)] and equivalent width of the hydrogen absorption stellar lines are given in Table 2, along with the uncorrected Hβ fluxes.

3 PHYSICAL CHARACTERISTICS AND ELEMENT ABUNDANCES

To determine element abundances, we follow generally the procedures of Izotov et al. (1994) and Izotov et al. (2006a). We adopt a two-zone photoionized H II region model: a high-ionization zone with temperature T_e(O III), where the [O III], [Ne III] and [Ar IV] lines originate, and a low-ionization zone with temperature T_e(O II), where the [N II], [O II], [S II] and [Fe II] lines originate. As for the [S II] and [Ar II] lines, they originate in the intermediate zone between the high- and low-ionization regions. The temperature T_e(O III) is calculated using the [O III] λ4363/(λ4959 + λ5007) ratio. To take into account the electron temperatures for different

1 IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
| Line          | J0905+0335 | J0920+5234 | J1016+3754 | J1044+0353 | J1050+1538 | J1053+5016 |
|--------------|------------|------------|------------|------------|------------|------------|
| 3188 HeⅠ     | 3.24±0.71  | 4.43±0.71  | 1.82±0.39  | 3.44±0.30  | –          | 2.07±0.46  |
| 3203 HeⅠ     | 1.78±0.57  | –          | –          | 0.82±0.17  | –          | –          |
| 3426 [NeⅤ]  | <0.55      | <0.25      | 0.58±0.15  | 0.61±0.15  | <0.23      | <0.17      |
| 3712 HⅠ      | 1.42±0.38  | 2.91±0.41  | 1.47±0.16  | 1.77±0.18  | 1.84±0.26  | 2.61±0.31  |
| 3727 [OⅢ]   | 104.24±1.73| 128.98±2.02| 63.96±0.98 | 30.86±0.51 | 119.78±1.88| 145.59±2.24|
| 3750 HⅡ      | 3.06±0.38  | 3.83±0.35  | 2.23±0.16  | 3.35±0.16  | 3.60±0.29  | 3.34±0.25  |
| 3770 HⅠ      | 3.47±0.39  | 4.54±0.32  | 3.03±0.17  | 4.03±0.16  | 4.07±0.29  | 4.28±0.25  |
| 3797 HⅠ      | 5.04±0.40  | 5.56±0.32  | 4.16±0.18  | 5.63±0.17  | 5.78±0.29  | 5.29±0.24  |
| 3820 HeⅠ     | 0.66±0.23  | 1.03±0.13  | 0.73±0.10  | 0.77±0.06  | 1.08±0.16  | 0.59±0.11  |
| 3835 HⅨ      | 6.87±0.39  | 7.87±0.30  | 6.38±0.18  | 7.61±0.19  | 7.86±0.29  | 7.43±0.25  |
| 3868 [NeⅣ]  | 46.62±0.82 | 42.84±0.69 | 36.94±0.57 | 35.68±0.57 | 55.55±0.90 | 48.52±0.76 |
| 3889 HeⅣ+HⅧ | 21.12±0.52 | 19.87±0.41 | 19.77±0.34 | 21.11±0.36 | 20.49±0.42 | 19.58±0.37 |
| 3968 [NeⅢ]  | 39.68 [NeⅢ]|             |             |             |             |             |
| 4388 HeⅠ     | 0.57±0.23  | 0.57±0.13  | 0.73±0.10  | 0.77±0.06  | 1.08±0.16  | 0.59±0.11  |
| 4711 [ArⅣ]  | 1.46±0.19  | 0.63±0.10  | 0.87±0.08  | 1.34±0.06  | 0.91±0.12  | 0.68±0.08  |
| 4861 Hβ      | 100.00±1.55| 100.00±1.47| 100.00±1.43| 100.00±1.45| 100.00±1.47| 100.00±1.46|
| 4921 HⅣ      | 0.97±0.19  | 1.22±0.12  | 0.78±0.06  | 1.10±0.06  | 1.30±0.13  | 0.93±0.08  |
| 4959 [OⅣ]   | 175.43±2.66| 181.47±2.65| 146.09±2.09| 141.58±2.05| 216.01±3.14| 198.09±2.87|
| 5007 [OⅦ]   | 526.29±6.55| 541.11±7.86| 428.87±6.11| 415.16±5.98| 644.11±9.34| 586.88±8.47|
| 5015 HeⅠ     | –          | –          | 2.24±0.08  | –          | –          | 2.07±0.11  |
| (C/Hβ)      | 0.000      | 0.000      | 0.000      | 0.020      | 0.180      | 0.000      |
| F(Hβ)       | 75.87      | 201.20     | 474.50     | 327.50     | 182.87     | 253.80     |
| EW(Hβ)/Å     | 116.4      | 139.1      | 96.7       | 257.8      | 198.5      | 127.8      |
| EW(abs)/Å    | 0.0        | 1.4        | 0.0        | 0.8        | 0.0        | 0.9        |

Table 2. Extinction-corrected emission-line fluxes.\(^a\)

\(^a\) Line fluxes are corrected for Galactic extinction and interstellar absorption with A(3968) = 0.33, A(6563) = 0.21. Column 1: line; Column 2: extinction-corrected flux (erg s\(^{-1}\) cm\(^{-2}\)).
ions, we have used the expressions of Izotov et al. (2006a). Since our observations cover only the blue part of the optical spectrum, the [S II] \(\lambda\lambda 6717, 6731\) emission lines usually used to determine the electron number density \(N_e(\text{S II})\) were not available. Therefore, we set \(N_e(\text{S II}) = 10^3\ cm^{-3}\). The low-density limit for abundance determinations should hold as long as \(N_e\) is less than \(10^4\ cm^{-3}\). Ionic and total heavy element abundances for the 12 BCDs observed with the MMT are derived in the manner described in Izotov et al. (2006a). The electron temperatures \(T_e(\text{O} III), T_e(\text{O} II)\), ionic and total heavy element abundances, and ionization correction factors (ICFs) for unseen stages of ionization are shown in Table 3. The oxygen abundances are given in Table 4. They are generally low, in the range \(12 + \log(O/H) = 7.43\pm8.02\), corresponding to heavy element mass fractions between 1/19 and 1/5 \(Z_{\odot}\) with the solar calibration of Asplund et al. (2009). The Ne/O and Fe/O abundance ratios are in the range of abundance ratios for BCDs (e.g. Izotov et al. 2006a).

### 4 HARD IONIZING RADIATION AND ORIGIN OF THE [NE V] \(\lambda 3426\) EMISSION

#### 4.1 Observed properties

The spectroscopic characteristics of the 12 observed BCDs are shown in Table 4. It contains the galaxy name, the redshift \(z\), the oxygen abundance \(12 + \log(O/H)\), the equivalent width EW(H\(\beta\)) of the H\(\beta\) emission line, the extinction-corrected fluxes of the H\(\beta\), He II \(\lambda 4686\) and [Ne V] \(\lambda 3426\) emission lines, the logarithm of the extinction-corrected H\(\beta\) luminosity, and the FWHM of the H\(\beta\), He II \(\lambda 4686\) and [Ne V] \(\lambda 3426\) emission lines. For comparison, we also show data from the literature for the three BCDs known previously to have [Ne V] \(\lambda 3426\) emission. For the present sample, Table 4 shows that [Ne V] \(\lambda 3426\) emission is present in five out of 12 BCDs, increasing the total number of known BCDs with [Ne V] \(\lambda 3426\) emission.
suggest that the non-detection is simply due to the faintness of the spectra with the $\text{[Ne V]} \lambda 0858$. The insets in each panel show the expanded part of the spectrum with a lower signal-to-noise ratio. These are derived from the $\text{[S II]} \lambda 6731$ flux ratio in the SDSS spectra, as the MMT spectra do not cover the red wavelength range.

In Table 4 we show in Fig. 2 the redshift-corrected spectra of the five BCDs with detected $\text{[Ne V]} \lambda 3426$ emission. The three dotted vertical lines are the galaxy J1426$+\gamma$0132, J1202$+\gamma$0110, J1423$+\gamma$1202, J1016$+\gamma$1044, and J0905$+\lambda 3426$ emission. The three dotted vertical lines are the galaxy J1426$+\gamma$1202, J1016$+\gamma$1044, and J0905$+\lambda 3426$ emission. On the other hand, the three dotted vertical lines are the galaxy J1426$+\gamma$1202, J1016$+\gamma$1044, and J0905$+\lambda 3426$ emission. In all eight BCDs the number fraction of the AGN $\text{[Ne V]} \lambda 3426$ emission is in line with the conclusions of Guseva et al. (2000) and Thuan & Izotov (2005) who found that the nebular HeII line emission is stronger in BCDs with lower metallicity, which would enhance the probability of detecting $\text{[Ne V]} \lambda 3426$ emission. On the other hand, there is no clear difference between the equivalent widths EW(Hβ) which measure the age of the starburst, and luminosities $L$(Hβ) of the Hβ emission line of BCDs with $\text{[Ne V]} \lambda 3426$ emission and of those without.

We also do not find any difference in the electron number density $N_e$ (S ii) (not shown in Table 4) between the two sets of galaxies. These are derived from the $\text{[S II]} \lambda 6717/\lambda 6731$ flux ratio in the SDSS spectra, as the MMT spectra do not cover the red wavelength range.

4.2 Origin of the hard radiation

4.2.1 AGNs

Izotov et al. (2004b) and Thuan & Izotov (2005) have analysed some possible sources of the hard ionizing radiation responsible for the H II and especially the $\text{[Ne V]} \lambda 3426$ emission. Although in normal galaxies, $\text{[Ne V]} \lambda 3426$ emission is usually attributed to the presence of an AGN, those authors rule out such a presence because other emission lines usually associated with AGN activity are not seen. We have run CLOUDY (version v10.00) models (Ferland et al. 1998) with an ionizing spectrum which includes both stellar (Leitherer et al. 1999) and AGN, those authors rule out such a presence because other emission lines usually associated with AGN activity are not seen. We have run CLOUDY (version v10.00) models (Ferland et al. 1998) with an ionizing spectrum which includes both stellar (Leitherer et al. 1999) and AGN (Mathews & Ferland 1987) ionizing radiation. We found that, to account for the observed strengths of both the $\text{[Ne V]} \lambda 3426$ and $\text{He II} \lambda 4686$ emission lines, the number fraction of the AGN ionizing photons should be $\lesssim 10$ per cent of the number of stellar ionizing photons. Thus, we cannot rule out the presence of a non-thermal source of ionization in the studied galaxies.

4.2.2 High-mass X-ray binaries

The energy of the photons that produce $\text{Ne}^{+4}$ ions is in the extreme-UV and soft X-ray range. Thus, high-mass X-ray binaries (HMXBs) may play a role. Izotov et al. (2004b) have estimated that the X-ray
luminosity required to reproduce the [Ne v] emission in the BCD Tol 1214–277 at photon energies greater than 0.14 keV should be $L_X = 10^{39}$–$10^{40}$ erg s$^{-1}$. Unfortunately, out of the eight known galaxies with [Ne v] emission, only SBS 0335–052 has Chandra X-ray observations (Thuan et al. 2004). For this BCD, it is found that more than 90 per cent of its 0.5–10 keV flux comes from a point source with a luminosity of $3.5 \times 10^{39}$ erg s$^{-1}$. If that point source is composed of a single object, then its luminosity would place it in the range of the so-called ultraluminous X-ray sources. However, Thuan & Izotov (2005) did not consider HMXBs as the main mechanism for producing [Ne v] emission. The reason is that there are other BCDs, such as I Zw 18 (Thuan et al. 2004) and Mrk 59 (Thuan et al., in preparation) that are known to contain HMXBs, but do not show [Ne v] emission.

4.2.3 Stars

Using photoionization H ii models, Schaerer & Stasińska (1999) have concluded that both the He ii and [Ne v] emission in BCDs could be explained by the hard ionizing radiation produced by WR stars. On the other hand, Thuan & Izotov (2005) have found that stellar radiation, including that of WR stars, is too soft for producing He ii $\lambda 4686$ emission with a flux above 0.1–1 per cent that of H$\beta$. To resolve this disagreement, we have run a series of CLOUDY models with pure stellar ionizing radiation. We have adopted the ionizing spectral energy distribution from STARBURST99 models with a heavy element mass fraction $Z = 0.001$ (Leitherer et al. 1999), corresponding to an oxygen abundance $12 + \log (O/H) = \sim 7.6$. We find that a detectable He ii $\lambda 4686$ emission line is present only in H ii region models powered by starbursts in the very short age range between 3.4 and 3.6 Myr. Furthermore, the maximum flux of this line is $\sim 0.5$ per cent that of H$\beta$, several times smaller than the observed flux. The discrepancy is considerably worse in the case of [Ne v] $\lambda 3426$ emission. Moreover, the broad WR bump at $\lambda 4650$ is present only in the spectrum of J1423+2257. It is absent in the spectra of the other four BCDs with [Ne v] $\lambda 3426$ emission. This is in line with the conclusions of Guseva et al. (2000) and Shirazi & Brinchmann (2012) who also did not find a clear correlation between the presence of WR and nebular He ii emission.

Thuan & Izotov (2005) found that it is possible, in principle, to reproduce the observed He ii $\lambda 4686$ and [Ne v] $\lambda 3426$ emission-line fluxes by models of low metallicity ($Z \lesssim 10^{-7}$) massive ionizing stars (Schaerer 2002, 2003). However, such models of Population III stars would predict equivalent widths of H$\beta$ emission line that are several times larger than those observed. Thus, neither models of normal stars, nor of WR stars, nor of primordial stars are able to reproduce the observed high-ionization line fluxes.

4.2.4 Fast radiative shocks

One of the most promising explanations for the hard radiation and the high-ionization emission lines in BCDs is the presence of the fast radiative shocks produced by supernovae (SNe). Izotov et al. (2004b) and Thuan & Izotov (2005) using the shock models of Dopita & Sutherland (1996) concluded that radiative shocks with velocities of $\sim 450$ km s$^{-1}$ can account for the observed fluxes of both the He ii $\lambda 4686$ and [Ne v] $\lambda 3426$ emission lines if the contribution of the shocks to the observed flux of the H$\beta$ emission line is a few per cent that of the stars. However, only shocks propagating in an interstellar medium (ISM) with solar metallicity were considered by Dopita & Sutherland (1996).

Since the work of Thuan & Izotov (2005), a new grid of radiative shock models has been calculated by Allen et al. (2008) for an ISM with solar, Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) metallicities, and a wide range of shock velocities going from 100 to 1000 km s$^{-1}$. We now examine whether these models are able to reproduce the observed fluxes of the high-ionization emission lines in our BCDs. However, a direct comparison of the models with the observations is not straightforward because: (1) the dominant source of ionization in BCDs is stellar emission, which would mask the effect of shocks on the emission-line fluxes; (2) most of the shock models were calculated for shocks propagating in a neutral or weakly ionized ISM, while we expect shocks in BCDs to propagate in an ISM fully ionized by massive stellar clusters and containing relatively high ionization species like O iii, Ne iii, Ar iv. This is evidenced by the strong emission lines of these ions seen in the spectra of the BCDs studied here (Fig. 2). We would then expect the emission lines of low-ionization species like [O ii] $\lambda 3727$ not to be affected by shocks, as they may originate in regions different from those where shocks propagate. Therefore, these cannot be used for shock diagnostics; (3) it is likely that the signatures of several shocks with different velocities are seen in the integrated spectra of BCDs. Indeed, Izotov et al. (1996) and Izotov, Thuan & Guseva (2007) have shown that the H$\beta$, [O ii] $\lambda 4959$, $\lambda 5007$, and H$\alpha$ emission lines in some BCDs exhibit broad components, with FWHMs of $\sim 1000$–2000 km s$^{-1}$ and fluxes of $\sim 1–2$ per cent of the narrow component fluxes. This broad emission is likely produced in...
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Figure 2. Redshift-corrected spectra of galaxies with [Ne\textsuperscript{v}] λ\textsuperscript{3426} \AA \ emission. The vertical dotted lines show the locations (from the left-hand to right-hand side) of the [Ne\textsuperscript{v}] λ\textsuperscript{3426} \AA, [Fe\textsuperscript{v}] λ\textsuperscript{4227} \AA and He\textsuperscript{II} λ\textsuperscript{4686} \AA emission lines, respectively. The insets show expanded parts of the spectra in the wavelength range 3380–3470 \AA. The [Ne\textsuperscript{v}] λ\textsuperscript{3426} \AA emission line is marked by a vertical dotted line.

the adiabatic shocks propagating with velocities of several thousand km s\textsuperscript{−1} (e.g. Chevalier 1977). Similar broad components of H\textbeta, and [O\textsuperscript{III}] λ\textsuperscript{4959}, λ\textsuperscript{5007} are observed in the spectra of some of the BCDs studied in this paper, such as J1044+0353 and J1545+0858 (Fig. 2). On the other hand, the He\textsuperscript{II} and [Ne\textsuperscript{v}] emission likely arises in the pre-shock and compressed post-shock regions of slower radiative shocks.

In Fig. 3, we show from the top to bottom the predicted I(He\textsuperscript{II} λ\textsuperscript{4686})/I(H\textbeta), I([Ne\textsuperscript{v}] λ\textsuperscript{3426})/I(H\textbeta), I([O\textsuperscript{III}] λ\textsuperscript{4959})/I(H\textbeta) and I([Ne\textsuperscript{v}] λ\textsuperscript{3426})/I(He\textsuperscript{II} λ\textsuperscript{4686}) emission-line flux ratios for the precursor, shock and combined precursor+shock models (from the left-hand to right-hand side) as a function of the shock velocity v\textsubscript{sh}. Models with solar, LMC and SMC metallicities are shown by a black solid line, a red dashed line and a green dotted line, respectively. All models have a number density of the ambient gas \(N_e = 1\text{ cm}^{-3}\), as the grid of models of Allen et al. (2008) for different metallicities was calculated only for that density. However, we have checked from the solar metallicity models, which were calculated for a range of \(N_e\), that the dependence of the emission-line flux ratios on \(N_e\) is weak in the range \(N_e = 0.1–10^3\text{ cm}^{-3}\). The shaded regions indicate the range of the observed emission-line flux ratios in the BCDs with detected [Ne\textsuperscript{v}] λ\textsuperscript{3426} emission.

Inspection of Fig. 3 shows that the predicted I(He\textsuperscript{II} λ\textsuperscript{4686})/I(H\textbeta) and I([Ne\textsuperscript{v}] λ\textsuperscript{3426})/I(H\textbeta) line ratios are generally considerably larger than the observed ones. Agreement is only possible in the very narrow range of shock velocities, v\textsubscript{sh} < 200 km s\textsuperscript{−1}. To have agreement for higher shock velocities, one would have to assume that the contribution of the shock ionizing radiation to the excitation of the H\textbeta emission line is small, not exceeding \(≤ 10\) per cent that of the stellar ionizing radiation. This would be a natural assumption since the studied BCDs contain numerous hot O stars, producing copious amounts of ionizing photons. There is another problem with the shock models with v\textsubscript{sh} < 200 km s\textsuperscript{−1}. While the modelled line flux ratios in Figs 2(c), (f) and (l) are comparable to the observed ratios, implying that shocks can be the only source of ionization, there is no such good agreement between the predicted and observed emission-line ratios of other species. In particular, the predicted [O\textsuperscript{III}] λ\textsuperscript{4959}/H\textbeta flux ratios (Fig. 2i) are several times lower than the observed ones. In fact, the shock models with a SMC oxygen abundance of 12 + log (O/H) = 8.1 underpredict this ratio over the entire range of shock velocities. For the lower oxygen abundances that are characteristic of our BCDs, the discrepancy would be even worse. Therefore, we conclude that the dominant source of ionization for the majority of the species in the BCDs studied here is stellar radiation, with the exception of the high-ionization species which would require an \(≤ 10\) per cent contribution from shock radiation.

The observed I([Ne\textsuperscript{v}] λ\textsuperscript{3426})/I(He\textsuperscript{II} λ\textsuperscript{4686}) flux ratio is in the range 0.2–0.5 (Table 4). If a single shock is assumed, then this range corresponds to shock velocities of \(300–500\) km s\textsuperscript{−1} (Fig. 3l). However, the situation is more complicated when there are several shocks superposed on one another. This is to be expected in our...
Figure 3. Dependences of various emission-line fluxes on the shock velocity $v_{sh}$ according to the radiative shock models of Allen et al. (2008). Only data for shocks propagating through a medium with a number density $N_e = 1 \text{ cm}^{-3}$ and a metallicity equal to that of the Sun (black solid lines), of the LMC (red dashed lines) and of the SMC (green dotted lines) are shown. From the left-hand to right-hand side are shown model predictions for the precursor, the shock and the combined precursor+shock, respectively. The panels from the top to bottom show the line flux ratios $I(\text{He II} \lambda 4686)/I(\text{H}\beta)$, $I(\text{[Ne V]} \lambda 3426)/I(\text{H}\beta)$, $I(\text{[O III]} \lambda 4959)/I(\text{H}\beta)$ and $I(\text{[Ne V]} \lambda 3426)/I(\text{He II} \lambda 4686)$, respectively.

BCDs which contain a large number of massive stars and hence many supernova remnants. The modelled $I(\text{He II} \lambda 4686)/I(\text{H}\beta)$ and $I(\text{[Ne V]} \lambda 3426)/I(\text{H}\beta)$ flux ratios would be both in agreement with the observed ratios if the fraction of the $\text{H}\beta$ flux produced by shocks is $\sim 10$ per cent that produced by stellar ionizing radiation, in the case of LMC and SMC metallicities (Figs 3c and f), and if shock velocities are in the 300–500 km s$^{-1}$ range. These shocks produce an appreciable amount of extreme-UV photons, but at higher X-ray energies of $\sim 1$ keV, the ionizing flux is predicted to decrease considerably (e.g. fig. 2 in Allen et al. 2008). Therefore, no appreciable X-ray emission is expected from our BCDs. Unfortunately, we cannot check this prediction as none of the BCDs in Table 4 has X-ray observations, except for the brightest one, SBS 0335$-$052E, where weak diffuse X-ray emission, accounting for 10 per cent of the total X-ray emission, was detected. The other 90 per cent comes from an ultraluminous X-ray binary, as described before (Thuan et al. 2004).

4.2.5 Pre-shock and shock regions

As for the pre-shock (precursor) and shock regions, they contribute comparably to the excitation of $\text{He II}$ and $\text{[Ne V]}$ emission, for $v_{sh} \sim 300–500$ km s$^{-1}$. However, we would expect a width difference in the lines arising from these regions. The pre-shock region is less disturbed, so the widths of the lines produced in that region should be narrow, of $\lesssim 50–100$ km s$^{-1}$. On the other hand, lines produced in...
the shocked region would be broader. However, the widths of these lines would depend on the characteristic time of thermalization, resulting in the highest width if the post-shock region is thermalized. In any case, the post-shock thermal velocities would be lower than the shock velocity.

In Table 4, we show the FWHMs of the Hβ, He I λ4686 and [Ne V] λ3426 emission lines. They are all very similar, ~200–250 km s⁻¹, corresponding to a velocity dispersion σ = FWHM/2.3 ≲ 100 km s⁻¹, significantly lower than the shock velocity. However, we point out that the emission lines in the MMT spectra are nearly unresolved, so that the measured widths are mainly instrumental. Izotov et al. (2006b), using higher resolution VLT/GIRAFFE observations of SBS 0335−052E, have measured the FWHMs of Hβ and He II λ4686 to be, respectively, ~90 and ~140 km s⁻¹. This difference in the FWHM is natural, as the Hβ emission line is produced mainly in the undisturbed gas ionized by stars, while He II λ4686 emission arises both in the pre-shock and post-shock ISM. Unfortunately, the observations of Izotov et al. (2006b) do not cover the near-UV range, and hence no high spectral resolution data for [Ne V] λ3426 are available.

5 CONCLUSIONS

We present MMT spectroscopic observations in the wavelength range 3200−5200 Å of 12 BCD galaxies. Our aim was to detect the high-ionization emission line [Ne V] λ3426 Å and to study the excitation mechanisms of this emission. Our main results are as follows:

1. The [Ne V] λ3426 Å emission line was detected in five BCDs. Adding the three BCDs known previously to have [Ne V] emission (Izotov et al. 2004b; Thuan & Izotov 2005), there is now a total of eight BCDs known to possess this property.

2. [Ne V] λ3426 Å emission was found only in galaxies with low oxygen abundance [12 + log (O/H) = 7.3−7.7] and showing relatively strong He II λ4686 Å emission ( ≳ 2 per cent of the Hβ emission-line flux). The [Ne V] λ3426/He II λ4686 flux ratio ranges between 0.2 and 0.5. On the other hand, there is no significant correlation of the [Ne V] flux with the equivalent width EW(Hβ) and the luminosity L(Hβ) of the Hβ emission line.

3. The [Ne V] and He II emission in the BCDs cannot be produced by ionizing radiation from high-mass X-ray binaries or massive main-sequence stars, in agreement with the conclusions from previous studies. WR stars are also ruled out. Out of five BCDs with detected [Ne V] λ3426 Å emission, broad WR emission was detected only in one galaxy.

4. The observed [Ne V] λ3426/He II λ4686 flux ratio can be reproduced in models with either AGN or radiative shock ionizing radiation. In the case of AGNs, the number fraction of the AGN ionizing photons should be ≲ 10 per cent of the number of stellar ionizing photons.

Another likely ionizing source for the [Ne V] and He II emission is shocks produced by supernovae. However, comparison with shock models is not straightforward because: (1) we likely observe the superposition of an ensemble of SN remnants with various shock velocities, while shock models are calculated for one given shock velocity; and (2) the main source of ionization of the lower ionization species (including hydrogen) is stellar radiation, thus excluding a direct comparison of the observed flux ratios of both high- and low-ionization species with shock model predictions. Therefore, the only constraint on shock models is the [Ne V] λ3426/He II λ4686 flux ratio. We find that the observed range of this flux ratio is consistent with models of radiative shocks if shock velocities are in the 300−500 km s⁻¹ range, and if the shock ionizing contribution is also ~10 per cent of the stellar ionizing contribution. This conclusion is in agreement with previous findings by Izotov et al. (2004b) and Thuan & Izotov (2005). Faster shocks, likely adiabatic, with velocities ≳ 1000−2000 km s⁻¹ are also present in our BCDs, as suggested by the low-intensity broad components of the Hβ and [O III] λ4959, 5007 Å emission lines seen in some objects.

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