

# Discovery of the high-ionization emission line [Ne V] $\lambda$ 3426 in the blue compact dwarf galaxy Tol 1214–277<sup>\*</sup>

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**Abstract.** The discovery of the high-ionization [Ne V]  $\lambda$ 3426 Å emission line in the spectrum of the blue compact dwarf (BCD) galaxy Tol 1214–277 is reported. The detection of this line implies the presence of intense ionizing X-ray emission with a luminosity  $L_x$  in the range  $10^{39}$ – $10^{40}$  erg s<sup>-1</sup>. Such a high X-ray luminosity cannot be reproduced by models of massive stellar populations. Other mechanisms, such as fast shocks or accretion of gas in high-mass X-ray binaries need to be invoked to account for the high intensity of the [Ne V]  $\lambda$ 3426 Å emission line.

**Key words.** galaxies: abundances – galaxies: dwarf – galaxies: evolution – galaxies: compact – galaxies: starburst – galaxies: stellar content – galaxies: individual Tol 1214–277

## 1. Introduction

Tol 1214–277 is one of the best studied blue compact dwarf (BCD) galaxies in the Southern sky. Numerous spectroscopic observations of its brightest H II region (e.g., Kunth & Sargent 1983; Campbell et al. 1986; Pagel et al. 1992; Masegosa et al. 1994; Fricke et al. 2001; Izotov et al. 2001a) have revealed the very low oxygen abundance changing in the range of  $12 + \log O/H = 7.51$ – $7.55$ . This makes Tol 1214–277 a possible candidate for being a young unevolved galaxy (Fricke et al. 2001), suitable for the primordial helium abundance determination (Pagel et al. 1992; Izotov et al. 2001a).

The spectrum of the brightest H II region in Tol 1214–277 is characterised by strong nebular emission lines suggesting a very young age ( $\sim 3$  Myr) for the ionizing cluster. A strong He II  $\lambda$ 4686 emission line is a common property of low-metallicity BCDs (Guseva et al. 2000). Its presence in the spectrum of Tol 1214–277 implies the existence of hard ionizing radiation with  $\lambda < 228$  Å. However, the He II  $\lambda$ 4686 emission line in Tol 1214–277 is the strongest among known BCDs, reaching  $\sim 5\%$  of the H $\beta$  emission line flux and suggesting that the hard radiation in this galaxy is particularly intense. Further evidence for the presence of the hard radiation in Tol 1214–277 was found by Fricke et al. (2001) who discovered the [Fe V]  $\lambda$ 4227 Å emission line in its spectrum.

Until now, this line has been definitely detected in only two BCDs, Tol 1214–277 and SBS 0335–052 (Fricke et al. 2001; Izotov et al. 2001b). [Fe V] emission can be present only in the He<sup>+2</sup> zone of the H II region. The ionization potential of the Fe<sup>+3</sup> ion is 4.028 Rydberg and hence the Fe<sup>+4</sup> ion can be produced only by radiation with  $\lambda \lesssim 200$  Å. Fricke et al. (2001) and Izotov et al. (2001b) have discussed different mechanisms which can be responsible for the hard radiation in Tol 1214–277 and SBS 0335–052. They concluded that ionizing stellar radiation is too soft to explain the strong He II  $\lambda$ 4686 and [Fe V]  $\lambda$ 4227 emission lines. Other ionization sources, such as fast shocks and high-mass X-ray binary systems, need to be considered.

In this paper we report the discovery of the [Ne V]  $\lambda$ 3426 emission line in the spectrum of Tol 1214–277 based on new spectroscopic observations. This finding further supports the presence of a very highly ionized gas component in the brightest H II region of Tol 1214–277.

## 2. Observations and data reduction

Long-slit spectroscopic observations of Tol 1214–277 were carried out during two nights, on 24 and 25 April, 2003 with the ESO 3.6-m telescope (La Silla) in conjunction with the EFOSC spectrograph. The long slit with width of 1'' was centered on the brightest H II region at a position angle PA =  $-34^\circ.2$ . The grism #11 was used giving the wavelength range  $\lambda$ 3400– $\lambda$ 7400 and the spectral resolution of  $\sim 13.2$  Å (FWHM). The spatial scale along the slit of 0'.157 pixel<sup>-1</sup> was binned by

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<sup>\*</sup> Based on observations collected at the European Southern Observatory, Chile, ESO program 71.B-0032(A).



**Table 2.** Derived physical parameters of the H II region.

Parameter	Value
$T_e(\text{O III})(\text{K})$	$19\,380 \pm 250$
$T_e(\text{O II})(\text{K})$	$15\,500 \pm 180$
$T_e(\text{Ar III})(\text{K})$	$17\,780 \pm 210$
$T_e(\text{S III})(\text{K})$	$17\,780 \pm 210$
$N_e(\text{S II})(\text{cm}^{-3})$	$380 \pm 260$
$\text{O}^+/\text{H}^+(\times 10^5)$	$0.229 \pm 0.008$
$\text{O}^{+2}/\text{H}^+(\times 10^5)$	$3.190 \pm 0.100$
$\text{O}^{+3}/\text{H}^+(\times 10^5)$	$0.189 \pm 0.011$
$\text{O}/\text{H}(\times 10^5)$	$3.609 \pm 0.101$
$12 + \log(\text{O}/\text{H})$	$7.56 \pm 0.01$
$\text{Ne}^{+2}/\text{H}^+(\times 10^5)$	$0.401 \pm 0.013$
$\text{ICF}(\text{Ne})^a$	1.13
$\log(\text{Ne}/\text{O})$	$-0.90 \pm 0.02$
$\text{S}^+/\text{H}^+(\times 10^7)$	$0.273 \pm 0.018$
$\text{S}^{+2}/\text{H}^+(\times 10^7)$	$1.915 \pm 0.211$
$\text{ICF}(\text{S})^a$	3.45
$\log(\text{S}/\text{O})$	$-1.68 \pm 0.04$
$\text{Ar}^{+2}/\text{H}^+(\times 10^7)$	$0.590 \pm 0.039$
$\text{Ar}^{+3}/\text{H}^+(\times 10^7)$	$1.404 \pm 0.105$
$\text{ICF}(\text{Ar})^a$	1.00
$\log(\text{Ar}/\text{O})$	$-2.26 \pm 0.03$
$\text{He}^+/\text{H}^+$ (weighted mean)	$0.076 \pm 0.001$
$\text{He}^{+2}/\text{H}^+$ (from He II $\lambda$ 4686)	$0.005 \pm 0.000$
$\text{He}/\text{H}$	$0.081 \pm 0.001$

<sup>a</sup>ICF is the ionization correction factor.

and  $T_e(\text{O III})$  (Izotov et al. 1994), based on a fit to the photoionization models of Stasińska (1990). The temperature  $T_e(\text{O II})$  is used to derive the  $\text{O}^+$  and  $\text{S}^+$  ion abundances. For  $\text{Ar}^{+2}$  and  $\text{S}^{+2}$  we have adopted an electron temperature intermediate between  $T_e(\text{O III})$  and  $T_e(\text{O II})$  following the prescriptions of Garnett (1992). The electron number density  $N_e(\text{S II})$  is derived from the  $[\text{S II}] \lambda 6717/\lambda 6731$  flux ratio. The oxygen abundance is  $\text{O} = \text{O}^+ + \text{O}^{+2} + \text{O}^{+3}$ , where  $\text{O}^{+3}$  is derived from the equation  $\text{O}^{+3}/(\text{O}^+ + \text{O}^{+2}) = \text{He}^{+2}/\text{He}^+$ . Total abundances of other heavy elements were computed after correction for unseen stages of ionization as described in Izotov et al. (1994) and Thuan et al. (1995). Five He I emission lines  $\lambda$ 3889,  $\lambda$ 4471,  $\lambda$ 5876,  $\lambda$ 6678,  $\lambda$ 7065 were used to derive the electron number density  $N_e(\text{He II})$  and the optical depth  $\tau(\text{He I } \lambda 3889)$ , and to correct the He I emission line fluxes for the collisional and fluorescent enhancements according to Izotov et al. (1994, 1997). The singly ionized helium abundance  $\text{He}^+/\text{H}^+$  is derived as a weighted mean of the abundances obtained from the corrected He I  $\lambda$ 4471,  $\lambda$ 5876,  $\lambda$ 6678 line fluxes. The total helium abundance is  $\text{He}/\text{H} = \text{He}^+/\text{H}^+ + \text{He}^{+2}/\text{H}^+$ . The electron temperatures  $T_e(\text{O III})$ ,  $T_e(\text{S III})$ ,  $T_e(\text{O II})$  for the high-, intermediate- and low-ionization regions respectively, the electron number densities  $N_e(\text{S II})$ , ionization correction factors (ICF), ionic and total heavy element abundances are shown in Table 2.

Note that the determination of  $N_e$  from the  $[\text{S II}] \lambda 6717, 6731$  Å emission lines and of sulfur abundance from the  $[\text{S III}] \lambda 6312$  Å emission line is not very accurate because of the low spectral resolution of the spectrum. The spectral resolution

is too low to resolve the  $\text{H}\alpha$   $\lambda$ 6563 Å and  $[\text{N II}] \lambda$ 6583 Å emission lines. Therefore, the nitrogen abundance was not derived.

The oxygen abundance  $12 + \log(\text{O}/\text{H}) = 7.56 \pm 0.01$  for the brightest H II region is in fair agreement with  $12 + \log \text{O}/\text{H} = 7.52 \pm 0.01$  derived by Fricke et al. (2001) and  $7.54 \pm 0.01$  derived by Izotov et al. (2001a). Despite the uncertainties caused by the low spectral resolution, the abundance ratios  $\text{Ne}/\text{O}$ ,  $\text{S}/\text{O}$  and  $\text{Ar}/\text{O}$  are in good agreement with the previous abundance determinations in Tol 1214–277 and mean values obtained for a sample of the most metal-deficient BCDs (Izotov & Thuan 1999).

#### 4. High-ionization emission lines

Our observations confirm the presence of the  $[\text{Fe V}] \lambda$ 4227 Å and the strong He II  $\lambda$ 4686 Å emission lines (Fig. 1, Table 1). Furthermore, we have detected for the first time in a star-forming galaxy the  $[\text{Ne V}] \lambda$ 3426 Å and marginally the  $[\text{Ne V}] \lambda$ 3346 Å emission lines. The  $[\text{Ne V}] \lambda$ 3426 Å emission line is seen in all four spectra of Tol 1214–277 obtained during two nights. Its width in the averaged spectrum is smaller than that of other emission lines, although the line is broader in the spectrum obtained during the second night. This difference is apparently due to the noisy spectrum in the blue part and the weakness of the  $[\text{Ne V}] \lambda$ 3426 Å line.

To produce strong  $[\text{Ne V}] \lambda$ 3426 Å the ionizing radiation must be intense at  $\lambda \lesssim 128$  Å, because the ionization potential of the  $\text{Ne}^{+4}$  ion is 7.138 Rydberg. Using the flux ratio  $I(\lambda 3346 + \lambda 3426)/I(\text{H}\beta)$  from Table 1 and expressions from Aller (1984) we can estimate the fraction of the  $\text{Ne}^{+4}$  ions in the H II region. This ion exists in the inner  $\text{He}^{+2}$  zone where the electron temperature is expected to be higher than that derived from the O III forbidden lines. To derive the electron temperature and other physical parameters in the inner zone of Tol 1214–277, we use the CLOUDY code (version C94.00; Ferland et al. 1998). Adopting the effective temperature of the ionizing radiation  $T_{\text{eff}} = 50\,000$  K and CoStar stellar atmosphere models (Schaerer & de Koter 1997), we obtain  $T_e(\text{Ne V}) = 36\,000$  K or  $17\,000$  K higher than  $T_e(\text{O III}) = 19\,400$  K (Table 2). Then  $\text{Ne}^{+4}/\text{H}^+ = 8.3 \times 10^{-8}$  or  $\sim 2\%$  of the  $\text{Ne}^{+2}$  abundance.

We used Kurucz (Kurucz 1979) and CoStar stellar atmosphere models and calculated several spherically symmetric ionization-bounded H II region models which reproduce reasonably well the observed emission line fluxes of the  $\text{O}^+$ ,  $\text{O}^{+2}$ ,  $\text{Ne}^{+2}$ ,  $\text{S}^{+2}$ ,  $\text{Ar}^{+2}$  and  $\text{Ar}^{+3}$  ions. However, the observed  $[\text{Ne V}] \lambda$ 3426/ $[\text{Ne III}] \lambda$ 3868 flux ratio in Tol 1214–277 is  $\sim 10^4$  times higher than that predicted by the H II region models even in the case of the CoStar atmosphere models of the hottest main-sequence stars (model F1 with  $T_{\text{eff}} \approx 54\,000$  K; Schaerer & de Koter 1997). The difference between the observations and model predictions is even larger when Kurucz stellar atmosphere models are used.

We now estimate the X-ray luminosity required to reproduce the large observed intensity of Ne V emission. The  $\text{H}\beta$  luminosity  $L(\text{H}\beta) \approx 2.5 \times 10^{40}$  erg s $^{-1}$  in Tol 1214–277 corresponds to a number of ionizing photons  $\log Q_{\text{H}} \approx 52.7$  ( $Q_{\text{H}}$  is in s $^{-1}$ ). The derived value of  $\log Q_{\text{H}}$  is a lower limit.

It might be higher if, e.g., the H II region is density-bounded or the gas does not fully cover the ionizing source. Additionally, dust might be present. However, the density-bounded H II region models are likely excluded because the observed flux of the [O II]  $\lambda$ 3727 emission line is not reproduced by those models. We cannot exclude the presence of dust. However, its amount in Tol 1214–277 is likely small, as evidenced by the strong Ly $\alpha$  emission line (Thuan & Izotov 1997). Scaling the CoStar model F1 (Schaerer & de Koter 1997) to the derived  $Q_H$  value, we obtain a predicted X-ray luminosity  $L_x^{\text{mod}}(\lambda \lesssim 128 \text{ \AA}) \approx 10^{35} - 10^{36} \text{ erg s}^{-1}$ . However, since the observed [Ne v]  $\lambda$ 3426/[Ne III]  $\lambda$ 3868 flux ratio is  $\sim 10^4$  times larger than the model prediction, the soft X-ray luminosity of Tol 1214–277 should be as high as  $L_x^{\text{obs}} = 10^{39} - 10^{40} \text{ erg s}^{-1}$  to reproduce the observations.

Tol 1214–277 has not been observed in the X-ray range. However, the estimated  $L_x^{\text{obs}}$  is consistent with the 0.5–10 KeV (or 1–25  $\text{\AA}$ ) X-ray luminosity derived from *Chandra* observations of another BCD with high-ionization lines, SBS 0335–052 (Thuan et al. 2004). The large difference between  $L_x^{\text{obs}}$  and  $L_x^{\text{mod}}$  in Tol 1214–277 implies that the dominant source of soft X-ray emission cannot be normal massive main-sequence stars. Note that this source is likely to be compact and located in the inner part of the H II region to produce X-ray emission with a high ionization parameter. Fast shocks with the velocities of  $\sim 400 - 500 \text{ km s}^{-1}$ , contributing up to 10% of the H $\beta$  luminosity, can be responsible for the observed high fluxes of both the He II  $\lambda$ 4686  $\text{\AA}$  and [Ne v]  $\lambda$ 3346, 3326  $\text{\AA}$  emission lines (Dopita & Sutherland 1996). Another possibility is the ionizing radiation produced by the accretion of gas in high-mass X-ray binaries. This mechanism appears to be at work in SBS 0335–052 (Thuan et al. 2004). If additional mechanisms of ionization and heating are important in the H II region of Tol 1214–277 then the [O III]  $\lambda$ 4363 emission line may be enhanced resulting in the higher temperature  $T_e$ (O III). In this case the heavy element abundances shown in Table 2 may be underestimated.

## 5. Summary

New spectroscopic observations of the blue compact dwarf (BCD) galaxy Tol 1214–277 are presented which reveal for the first time in a star-forming galaxy the strong ( $\sim 2\%$  of H $\beta$ ) [Ne v]  $\lambda$ 3426  $\text{\AA}$  and probably the [Ne v]  $\lambda$ 3346  $\text{\AA}$  high-ionization lines. This finding implies the presence of intense ionizing X-ray emission in Tol 1214–277 from one or several compact sources which are not the usual massive stars.

Other mechanisms, such as fast shocks or gas accretion in high-mass X-ray binaries, can probably account for the large luminosity in the [Ne v]  $\lambda$ 3426  $\text{\AA}$  emission line. Because its metallicity is low and star-forming activity is high, Tol 1214–277 may be a good approximation to primordial galaxies, and its study can shed light on the physical conditions of high-redshift galaxies. In particular, we expect relatively strong high-ionization emission lines to be present in the spectra of primordial galaxies.

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## References

- Aller, L. H. 1984, *Physics of Thermal Gaseous Nebulae* (Dordrecht: Reidel)
- Campbell, A., Terlevich, R., & Melnick, J. 1986, *MNRAS*, 223, 811
- Dopita, M. A., & Sutherland, R. S. 1996, *ApJS*, 102, 161
- Ferland, G. J., Korista, K. T., Verner, D. A., et al. 1998, *PASP*, 110, 761
- Fricke, K. J., Izotov, Y. I., Papaderos, P., Guseva, N. G., & Thuan, T. X. 2001, *AJ*, 121, 169
- Garnett, D. R. 1992, *AJ*, 103, 1330
- Guseva, N. G., Izotov, Y. I., & Thuan, T. X. 2000, *ApJ*, 531, 776
- Izotov, Y. I., Chaffee, F. H., & Green, R. F. 2001a, *ApJ*, 562, 727
- Izotov, Y. I., Chaffee, F. H., & Schaerer, D. 2001b, *A&A*, 378, L45
- Izotov, Y. I., & Thuan, T. X. 1999, *ApJ*, 511, 639
- Izotov, Y. I., Thuan, T. X., & Lipovetsky, V. A. 1994, *ApJ*, 435, 647
- Izotov, Y. I., Thuan, T. X., & Lipovetsky, V. A. 1997, *ApJS*, 108, 1
- Kunth, D., & Sargent, W. L. W. 1983, *ApJ*, 273, 81
- Kurucz, R. L. 1979, *ApJS*, 40, 1
- Masegosa, J., Moles, M., & Campos-Aguilar, A. 1994, *ApJ*, 420, 576
- Pagel, B. E. J., Simonson, E. A., Terlevich, R. J., & Edmunds, M. G. 1992, *MNRAS*, 255, 325
- Stasińska G. 1990, *A&AS*, 83, 501
- Schaerer, D., & de Koter, A. 1997, *A&A*, 322, 598
- Thuan, T. X., & Izotov, Y. I. 1997, *ApJ*, 489, 623
- Thuan, T. X., Izotov, Y. I., & Lipovetsky, V. A. 1995, *ApJ*, 445, 108
- Thuan, T. X., Bauer, F. E., Papaderos, P., & Izotov, Y. I. 2004, *ApJ*, in press