A Universe of Dwarf Galaxies
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INVESTIGATING THE CHEMICAL HOMOGENEITY OF LOW-METALLICITY BLUE COMPACT DWARF GALAXIES USING INTEGRAL FIELD SPECTROSCOPY

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Abstract. It has been claimed in the past that in low-metallicity Blue Compact Dwarf (BCDs) galaxies, the N/O value is independent of metallicity (O/H ratio), implying the need to invoke a primary production of nitrogen in intermediate-mass stars, in addition to the secondary nitrogen produced from the CNO cycle in high-mass stars. In order to better understand this controversial issue we undertook an integral field spectroscopic study of the nebular gas within a sample of BCDs previously thought to have anomalously high N/O values. Here we present the results of this study for 3 BCDs: two with anomalous N/O values (Mrk 996 and UM 420) and one with more normal N/O values (UM 462). We describe in detail how we derived the physical conditions (Te, Ne) as a function of position within the galaxy, and as a consequence, how this revealed both revised metallicities and normal N/O ratios and uncovered one of the first clear evidences of nitrogen self-enrichment of an H II region from WR stars.

1 Introduction

Blue Compact Dwarf (BCD) galaxies provide a means of studying chemical evolution and star formation in low metalliciy environments in the nearby Universe. In general they are faint ($M_B > 18$), have blue optical colours, are typically small ($\lesssim 1\,$kpc) and experience bursts of star formation in relatively chemically unevolved environments, ranging from 1/2–1/50 solar metallicity (Kunth & Östlin 2000), and are therefore good analogues to high-z primordial galaxies.

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In contrast to the metallicity dependence of N/O at high metallicities (*i.e.* $12 + \log(\mathrm{O/H}) \geq 8.3$, where N is a secondary production element), studies have shown that for galaxies with $7.6 \leq 12 + \log(\mathrm{O/H}) \leq 8.3$ there can be considerable scatter in N/O. While a range of theories exist to explain this dispersion, such as the delayed release of N compared to α elements or the loss of heavy elements via galactic winds, one main theory suggests that within such galaxies, N is produced as a primary element by massive, short lived stars (Izotov *et al.* 1999). However, various problems exist with this theory, including there being no clear mechanism known to produce N in massive stars and the fact that BCDs are known to already host old stellar populations and hence low and intermediate-mass stars should also be releasing N into the ISM (Lopez-Sanchez *et al.* 2007). Interestingly, the majority of galaxies that display an increased N/O ratio also show the spectral signatures of Wolf-Rayet (WR) stars, suggesting that the N-rich winds from large numbers of WNL stars could also be a contributing factor.

In order to fully explore the complex physical, chemical and kinematical properties of these systems, it is crucial to gain spatially resolved spectroscopic information. This type of information has been limited in previously long-slit spectroscopic studies of H II galaxies. Here we present a summary of the results of two VLT-VIMOS Intergral Field Unit (IFU) studies; firstly of two perturbed BCDs UM 420 and UM 462, as presented in James *et al.* (2010) (J10 hereafter), and secondly of the highly anomalous BCD, Mrk 996, as presented in James *et al.* (2009) (J09 hereafter). Both Mrk 996 and UM 420 fall within a small sub-set of BCDs reported by Pustilnik *et al.* (2004) as having anomalously high N/O abundance ratios (∼0.5 dex) compared to BCDs of similar oxygen metallicity.

2 Emission line profiles and maps

Emission lines were measured using an automated fitting routine that fits an optimum number of Gaussian profiles by using the χ^2 value of the fit combined with the statistical F-test.

UM 420 & UM 462: All emission lines in the spectra of both UM 420 and UM 462 were optimally fitted with a single narrow Gaussian profiles. The UM 420 Hα flux map (Fig. 1, left) displays a double peak that defines two main star-forming (SF) regions. UM 462 (Fig. 1, right), however, displays a far more disrupted morphology with four peaks in Hα flux defining four main SF regions.

Mrk 996: It was found that in the spectra of Mrk 996 most high signal-to-noise (S/N) ratio emission line profiles consisted of a strong, narrow central Gaussian component (hereafter C1), superimposed on a very broad component (hereafter C2). Hα flux, radial velocity and FWHM maps of Mrk 996 are shown in Figure 2, for emission line components C1 and C2. Resultant optimised fits for line species (of interest in this publication) are as follows: *Single narrow* Gaussian – [S II] $\lambda\lambda$6717, 6731; *Single broad* Gaussian – [N II] λ5755, [O III] λ4363; *Double narrow/broad* Gaussian – all Balmer lines, [O III] $\lambda\lambda$4959, 5007. Our multi-component line analysis shows that only the broad (C2) component of the auroral [O III] λ4363 and [N II] λ5755 transitions are present, and only in the inner galaxy.

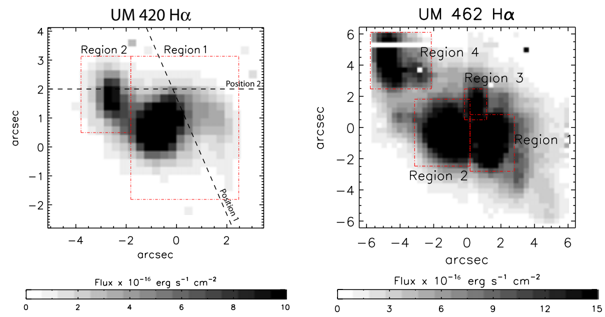

Fig. 1. Hα emission line maps; UM 420 (left) and UM 462 (right).

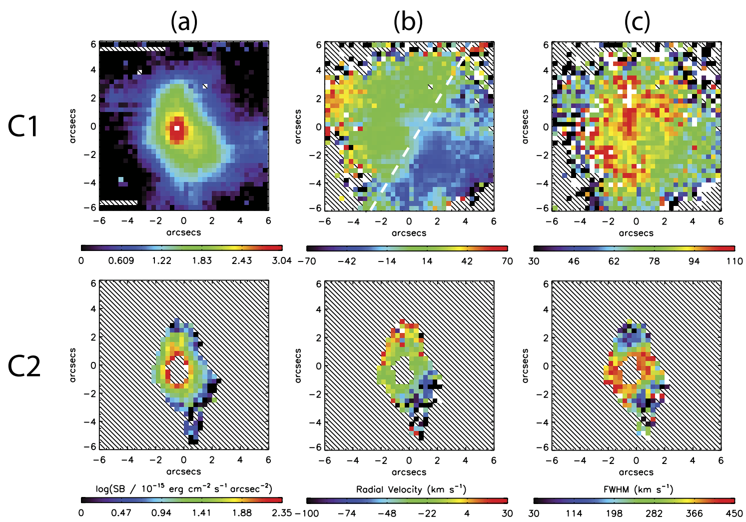

Fig. 2. Mrk 996: Hα (a) surface brightness, (b) radial velocity and (c) FWHM emission line maps of narrow C1 Gaussian component and broad C2 Gaussian component emission.

3 Physical conditions and chemical abundances

UM 420 & UM 462: Ionic abundances were computed from both emission line maps and from integrated spectra over each SF region. A graphical representation of the variations in elemental and ionic abundances between the SF regions within UM 420 and UM 462 is shown in J10 Figure 9. Average T_e and N_e values from the regions corresponding to peaks in Hα emission from UM 420 and UM 462 are given in Table 1. UM 420 shows minimal abundance variations are throughout, with elemental oxygen abundances corresponding to $\sim$0.35 $Z_\odot$ for both Regions 1 and 2. The nitrogen abundances of the two regions of SF are consistent within their uncertainties. The N/O ratios for both regions are consistent with those of

Table 1. Average T_e, N_e and select elemental abundances derived from IFU spectra of UM 420, UM 462 and Mrk 996.

Property	Um 420	UM 462	Mrk 996	
			C1	C2
T_e	$14\,000 \pm 1500$	$13\,700 \pm 350$	10,000	11,000
N_e	170 ± 80	90 ± 75	170	10^7
$12 + \log(\text{O/H})$	8.03 ± 0.13	8.03 ± 0.04	8.38 ± 0.8	8.36 ± 0.32
$12 + \log(\text{N/H})$	6.58 ± 0.45	6.18 ± 0.11	6.94 ± 0.55	8.23 ± 0.35
log (N/O)	-1.45 ± 0.60	-1.85 ± 0.15	-1.43	-0.13

other metal-poor emission line galaxies of similar oxygen metallicity (Izotov *et al.* 2006), and do not shown the nitrogen excess reported by Pustilnik *et al.* (2004). The oxygen abundance varies spatially across the different SF regions of UM 462. Four maxima in oxygen abundance are seen across the map, all aligning spatially with peaks in Hα emission. A maximum variation of 40% is seen between Region 1 (highest metallicity) and Region 3 (lowest). The mean oxygen abundance of the four identified SF regions in UM 462 corresponds to $\sim$0.25 $Z_\odot$. Regions 2, 3 and 4 have the same nitrogen abundance within the uncertainties. However, overall, the galaxy can be said to be chemically homogeneous, with no significant variation in chemical abundance (*i.e.* within 0.2 dex) throughout its SF regions.

Mrk 996 – a multi-component analysis: The multi-component emission lines from Mrk 996 must be taken into account when applying plasma diagnostic methods. The detection of separate narrow and broad line components opens up the possibility of determining separate T_es and N_es and conducting a separate abundance analysis for each. Figure 3 shows the abundance distributions in the directions from NE to SW and SE to NW that pass through the centre of Mrk 996 for the narrow component gas. A cut across the N/O ratio map of Mrk 996, shows log(N/O) $\simeq -1.5$ in the core, rising to $\simeq -1.2$ at a spot NE of the core. The origin of this trend is discussed in Section 3.1. The broad line region in the nuclear starburst is very dense ($10^7\,\text{cm}^{-3}$) whereas the narrow line component is of lower density ($\lesssim 10^3\,\text{cm}^{-3}$). The upwards revised oxygen metallicity of Mrk 996 is $>0.5\,Z_\odot$ ($12 + \log(\text{O/H}) \approx 8.37$) for both the narrow and broad component emission. The broad line region is nitrogen-enriched compared to the narrow line region by $\lesssim$1.3 dex. The S/O and Ar/O abundance ratios in the two components, as well as the N/O ratio in the *narrow* line component, are typical of those in H II galaxies and dwarf irregulars (*e.g.* Izotov *et al.* 2006). Table 1 lists the mean T_e, N_e and elemental abundances for the narrow and broad component gas.

3.1 Mrk 996: N enrichment from WR stars

The VIMOS IFU spectra of Mrk 996 also show a broad WR stellar feature at 4650 Å, attributable to a mixture of late-type WN and WC stars. The WR spectral signatures are seen to extend throughout the core region of Mrk 996 (J09 Fig. 20)

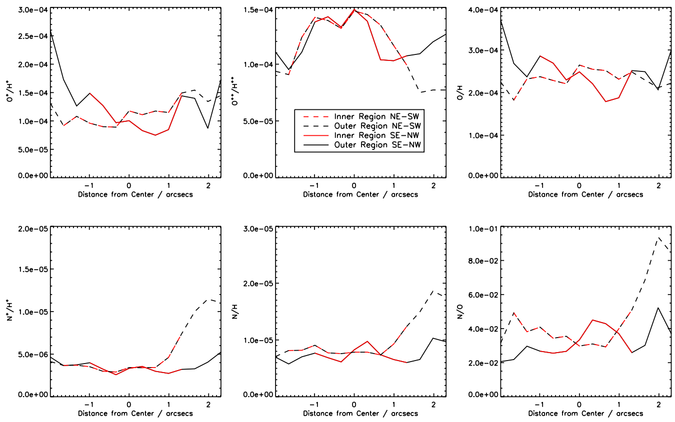

Fig. 3. Spatial variations in narrow component ionic and elemntal abundances across Mrk 996 obtained for $T_{\rm e} = 10,000\,{\rm K}$ and $N_{\rm e} = 170\,{\rm cm}^{-3}$.

and show excellent agreement with the spatial extent of the broad [O III] λ4363 emission (J09 Fig. 8).

Due to the powerful winds of WR stars, the spatial correlation of broad component emission and WR spectral features may not be surprising. Given the youth of the starburst region in Mrk 996 containing large numbers of young O ($\lesssim$150,000 O7V-type, as estimated from L(Hβ)) and WR-type stars, and the presence of very dense zones of gas (Sect. 3), it is possible that the broad line emission partly originates from a turbulent mixing layer forming on the surface of dense cool clumps which are subjected to irradiation and hydrodynamic ablation from the hot winds of young massive star clusters. If the presence of broad emission indicates that strong wind-clump interactions are taking place, then by extension, material from these interaction sites must be being stripped off and entrained into the cluster wind flows contributing to the N-enriched appearance of C2.

The mild two-fold increase over the mean narrow line N/H (Fig. 3) spatially correlates with a local peak in EW(Hβ) in a region where no WR stars are seen. This could mean that even though the narrow-line gas is fairly well mixed, some localised N-enrichment has already occurred in an area dominated by normal OB-type stars which is slightly younger than the nuclear starburst.

At present, only one other galaxy has been reported to display localised N-enrichment: NGC 5253. Deep VLT eschelle spectroscopy by Lopez-Sanchez *et al.* (2007) of this well studied starburst galaxy showed increased N/O ratio in the two central starburst regions and within one region the increase was isolated to the broad component emission exclusively. In support of the cases of both Mrk 996 and NGC 5253, a large study of 570 WR galaxies by Brinchmann *et al.* (2008) found that an overall increase in N/O is seen when comparing WR galaxies with a set of similar galaxies that show no WR features ($\Delta\log({\rm N/O})_{WR-nonWR} = 0.13\pm0.04$), when EW(H$\beta$) $< 100\,$Å, which they attribute to seeing the effect of WR winds on the ISM. However, it should be noted that increased N/O ratios are seen in many BCD-WR galaxies, but not all. This may be a result to two effects; firstly if the increase *is* due to pollution by WR stars then the enrichment would be very short lived and localised, thus making it difficult to detect and secondly, the definition of a WR galaxy is highly dependent on the aperture and exposure time of the observations.

4 Conclusions

Here we presented the combined results from two IFS studies of three blue compact dwarf galaxies: UM 420, UM 462 and Mrk 996. Both UM 420 and Mrk 996 were previously reported as having anomalously high N/O ratios for their respective metallicities, whereas UM 462 was known to have more normal N/O values. For all galaxies, we used emission line maps to spatially resolve their physical and chemical environments, in order to fully investigate any chemical inhomogeneities that may exist.

For both UM 420 and UM 462 the abundances of N and O were measured and O/H abundance ratio maps were created based on the direct method. We find no evidence for significant nitrogen or oxygen variations across the galaxies (at the 0.2 dex level), which would point to self-enrichment from nucleosynthetic products associated with recent massive star formation activity.

In the case of Mrk 996, our IFU analysis enabled a separate analysis of the narrow and broad emission line regions. The narrow-line N/O ratio in particular is exactly the value expected based on the galaxy's colour; its mean current value can be interpreted as the result of the slow release of nitrogen from the intermediate-mass stellar population over the last few Gyrs. On the other hand, the high N/O ratio in the broad line region of the inner galaxy is consistent with the presence of numerous evolved massive stars and can be attributed to the cumulative effect of their N-enriched winds. Thus Mrk 996 is one of only two galaxies where we have clear evidence of nitrogen self-enrichment of an H II region from WR stars, suggesting that the nitrogen enrichment seen in the low-metallicity gas of these BCDs is not due to primary nitrogen production, as suggested by current theories.

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