Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
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Is there any pristine gas in nearby starburst galaxies?

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Abstract. We derive the chemical composition of the neutral gas in the blue compact dwarf (BCD) Pox 36 observed with FUSE. Metals (N, O, Ar, and Fe) are underabundant as compared to the ionized gas associated with H II regions by a factor ~ 7. The neutral gas, although it is not pristine, is thus probably less chemically evolved than the ionized gas. This could be due to different dispersal and mixing timescales. Results are compared to those of other BCDs observed with FUSE. The metallicity of the neutral gas in BCDs seems to reach a lower threshold of $\sim 1/50\,Z_\odot$ for extremely-metal poor galaxies.

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1. Introduction

Within the chemical downsizing scenario, in which massive galaxies are the first to form stars at a high rate (e.g., Cen & Ostriker 1999), dwarf galaxies can remain chemically unevolved since their formation. It is thus possible that some dwarf galaxies in the nearby Universe still contain pristine gas (Kunth & Sargent 1986; Kunth *et al.* 1994). An important step in understanding the process of metal enrichment of galaxies is to study all the gaseous phases involved in the gas mixing cycle, in particular the neutral phase.

Metals from the neutral gas can be observed through resonant lines in the far-ultraviolet (FUV). Blue compact dwarfs (BCDs) are ideal targets because they display large amounts of H I gas (Thuan & Martin 1981), and because the massive stars provide strong FUV continuum. The FUSE telescope (Moos *et al.* 2000) allows the observation of absorption-lines of H I together with many metallic species such as N I, O I, Si II, P II, Ar I, and Fe II. The neutral gas chemical composition was derived in several BCDs, IZw18 (Aloisi *et al.* 2003; Lecavelier *et al.* 2004), NGC1705 (Heckman *et al.* 2001), Markarian 59 (Thuan *et al.* 2002), IZw36 (Lebouteiller *et al.* 2004), NGC625 (Cannon *et al.* 2004), and SBS0335-052 (Thuan *et al.* 2005). Results showed that the neutral gas of BCDs has already been enriched with metals up to an amount of $\gtrsim 1/50\,Z_\odot$. This "threshold" metallicity value could represent a minimal amount due to starburst episodes. The second most important result is that the metallicity of the neutral gas is systematically lower than that of the ionized gas, implying that the neutral phase has been probably less processed.

We analyzed the blue compact dwarf galaxy Pox 36 which, because of its low H I column density, shows absorption-lines weak enough to be safely considered as unsaturated. Results are compared to those of the other BCDs.

2. Overview

The spectral continuum is provided by the UV-bright massive stars in the galaxy. Absorption-lines from species along the line of sight are superimposed on the continuum. The line of sight intersects the ISM from the Milky Way and the ISM from Pox 36 itself. The redshift of Pox 36 makes it possible to separate easily the Local absorption system from the intrinsic one. Absorption lines from the Milky Way are easily identified at an almost null radial velocity.

The absorption system corresponding to the neutral ISM in Pox 36 is detected at a velocity of $v_n = 1058 \pm 10\,\mathrm{km\,s^{-1}}$. We do not detect any H_2 lines. The radial velocity inferred from far-UV absorption lines is smaller than the value of the ionized gas as probed by optical emission lines, being consistent with a different origin of the two gaseous phases. More surprisingly, v_n is also smaller than the velocity derived from the 21 cm H I line. However, it must be stressed that the regions probed are different in terms of extent (because of the beam size) and in terms of depth (because of dust extinction). Hence the comparison of the velocity inferred from the optical, radio, and FUV must be interpreted with care. Instead, we take the opportunity given by the wealth of spectral features provided in the FUSE wavelength range to compare the relative velocities of the various galaxy components. In addition to tracers of the neutral gas, we have indeed access to the warm photoionized gas through the S III line at 1012.49 Å (giving $v_i = 1102 \pm 20\,\mathrm{km\,s^{-1}}$) and to the stars through the C III photospheric line at 1175.6 Å ($v_{stars} = 1082 \pm 20\,\mathrm{km\,s^{-1}}$). Hence using consistent data (only limited by the wavelength calibration), we find that the neutral gas is most likely indeed blue-shifted compared to the stars and to the ionized gas.

3. Stellar contamination and H I column density

The FUV spectrum of most of the BCDs and giant H II regions studied so far with FUSE is dominated by O stars. This is indicative of a starburst age younger than $\sim$ 10 Myr (Robert *et al.* 2003). Because of the high temperature, hydrogen is mostly ionized, and only weak H I photospheric lines can be observed which contribute to the – already saturated – core of the interstellar H I absorption line. Hence FUV spectra toward young starbursts allow a precise determination of the interstellar H I content. Older starbursts ($\gtrsim$ 10 Myr) are dominated by B stars. Such stars have overall a more complex FUV spectrum than O stars because the degree of ionization is lower. For this reason, photospheric H I lines become prominent (Valls-Gabaud 1993). As an illustration, the H I lines from the Lyman series in the BCD Markarian 59 show "V-shaped" wings typical of B star photospheres (Thuan *et al.* 2002). Pox 36 shows a similar pattern. While Thuan *et al.* (2002) circumvented the problem by considering an artificial continuum to fit the profile of the H I lines, we decided to model the stellar absorption.

In order to reproduce the synthetic spectral continuum of Pox 36, we used the TLUSTY models for O and B stars (Lanz & Hubeny 2003; 2007) which provide detailed FUV absorption spectra. We choose to model the stellar spectrum of Pox 36 with a single stellar population. Since low-order Lyman lines (Lyα, Lyβ) are characterized by strong interstellar damping wings, interstellar H I dominates the global shape. On the other hand, cool stars contribute to prominent "V-wings" that are strongly constrained by the observed profile, especially of the high-order Lyman lines. We conclude that the stellar population contributing to the stellar H I profile is probably narrow around a given stellar type, in this case B0.

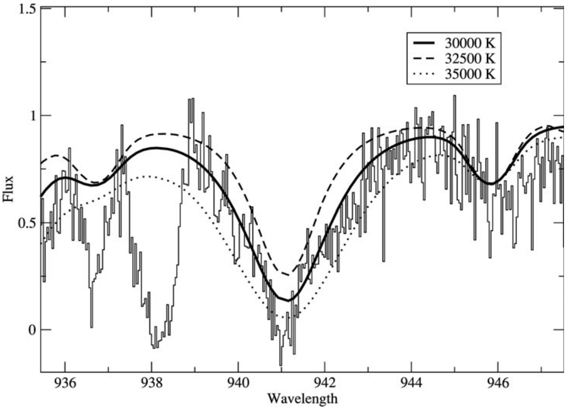

Figure 1. The Lyϵ line profile is dominated by stellar "V-wings" and gives a strong constraint on the photosphere temperature of the dominant stellar population. Models are drawn for a metallicity of $1/1000\,Z_{\odot}$, but the profile of stellar H I lines is unchanged for varying metallicities.

The wings of the stellar H I lines are strongly dependent on temperature. The best constraint is given by the high-order line of the Lyman serie since the interstellar contribution is saturated with no damping wings. Given the redshift of Pox 36 and the contamination by metallic lines from the Milky Way, Lyϵ is the cleanest H I line to constrain the temperature. The line profile gives a temperature of 30 000 K (Fig. 1), corresponding to a B0 class population.

Lyβ has prominent interstellar damped wings and can be used to constrain the interstellar H I column density if the stellar temperature is $\gtrsim$ 30 000 K, which is the case in Pox 36. After removing the stellar absorption component, we find $\log N$ (H I) $= 20.28 \pm 0.06$. The uncertainty is only statistical and does not include systematic errors on the stellar model. We estimate a total conservative error of ±0.3 dex.

Is this determination in agreement with the column density inferred from radio observations? Assuming an optically thin case and a distance of 20 Mpc, the integrated H I radio flux gives a mass of $M(\mathrm{H}) = 8.1 \times 10^{8}\,\mathrm{M}_{\odot}$. If the H I distribution is uniform, the average H I column density would be $\log N(\mathrm{H\,I}) \sim 20.7$. It must be stressed that the radio observation probes deeper lines of sight than those observed in the FUV. Hence, we could expect the H I column density measured in absorption to be roughly around half this determination, i.e., $\log N(\mathrm{H\,I}) \sim 20.4$. In addition, radio observations probe warm and cold neutral gas, while FUSE could observe mostly cold gas. As a conclusion, we estimate that the interstellar H I column density in Pox 36 is $\log N(\mathrm{H\,I}) = 20.3 \pm 0.4$ using Lyβ with conservative error bars.

4. Abundances

We derived metal column densities by fitting their profiles with Voigt profiles. We made the usual assumption of a single line of sight intersecting a medium with uniform properties (namely radial velocity, turbulent velocity, and column densities). The method to derive column densities from line profiles with FUSE is thoroughly discussed in Hébrard *et al.* (2002). Profiles are adjusted through a minimization of the χ^2 between the model and the observations. All the lines could be fit using simple Voigt profiles.

Abundances were then derived from column densities. It is the usual assumption to estimate the abundance of an element using the primary ionization state. We expect to find all elements with ionization potentials larger than that of hydrogen (13.6 eV) as

Table 1. Chemical abundances.

Element (tracer)	log (X/H)	$[X/H]_n^1$	$[X/H]_i^2$
N (N I)	-6.10 ± 0.42	-1.88 ± 0.42	-1.20 ± 0.06
O (O I)	-4.72 ± 0.41	-1.38 ± 0.41	-0.50 ± 0.05
Si (Si II)	-5.24 ± 0.47	-0.75 ± 0.47	...
P (P II)	-7.52 ± 0.47	-0.88 ± 0.47	...
Ar (Ar I)	-7.12 ± 0.47	-1.30 ± 0.47	-0.42 ± 0.06
Fe (Fe II)	-6.32 ± 0.42	-1.77 ± 0.42	-1.62 ± 0.11

Notes:
[1] Abundance in the neutral gas. [X/H] is defined as log (X/H) - log $(X/H)_\odot$, where log $(X/H)_\odot$ is the solar abundance. Solar abundances are from Asplund *et al.* (2005).
[2] Abundance in the ionized gas.

neutral atoms in the H I gas. This is the case for N, O, and Ar. On the other hand, Si, P, and Fe are mostly found as single-charged ions with negligible fractions of neutral atoms. Abundances are presented in Table 1.

It is clear that the neutral gas in Pox 36 is not pristine; it has already been enriched with heavy elements. This was expected since Pox 36 is more metal-rich than IZw18 and SBS0335-052 where no pristine gas has been found either (Lecavelier *et al.* 2004; Aloisi *et al.* 2003; Thuan *et al.* 2005).

Given its radial velocity, it seems that the neutral gas of Pox 36 is pushed away from the stellar clusters and their associated ionized gas. This is consistent with the gas being pushed by supernovae-driven shocks. The neutral gas cannot be enriched by the star-formation episode since we would expect a metallicity at least equal to or higher than that in the ionized gas of the H II regions. On the other hand, it is still possible that some of the atomic gas lies in front, being almost pristine. This would dilute the chemical abundances by adding H I without any metallic counterpart.

The final results (Table 1) show that N is underabundant by a factor ≈ 5 in the neutral gas of Pox 36 as compared to the ionized gas, while both O and Ar are underabundant by a factor ≈ 8. The relative agreement between the deficiency of N, O, and Ar in the neutral gas indicates that abundances of N and Ar are probably well determined, with only little ionization corrections required. Oxygen and argon are the best metallicity tracers available in the ionized gas, and agree with a metallicity of $\approx 1/3\,Z_\odot$ in this phase. Considering these 2 elements, we find that the metallicity in the neutral gas should be $\approx 1/22\,Z_\odot$, i.e., a factor ~ 7 below the value in the ionized gas. Our result in Pox 36 confirms those obtained for the other BCDs of the FUSE sample.

5. BCDs

We plot in Fig. 2 the elemental abundance [X/H] in the ionized gas and in the neutral gas of BCDs observed with FUSE. It can be seen that N and O (and Ar, not shown here) show identical trends, with a hint of a plateau at low metallicity and a positive correlation at higher metallicities. Part of the dispersion for [O/H] is probably due to saturation effects which could not be avoided in all cases. Part of the dispersion for [N/H] and [Ar/H] is probably due to ionization corrections. Since the trend is similar for N, O, and Ar, it seems that the corrections are on the same order for all the objects (probably within 0.5 dex), or that they are in fact negligible, as suggested by results of Pox 36.

A caveat exists in that the presence of foreground H I gas with no metals could dilute the metal abundances in the neutral gas. Therefore, except if the dilution factor is identical for all the sources, the presence of the plateau and of the correlation suggests that there is no significant dilution by metal-free H I gas.

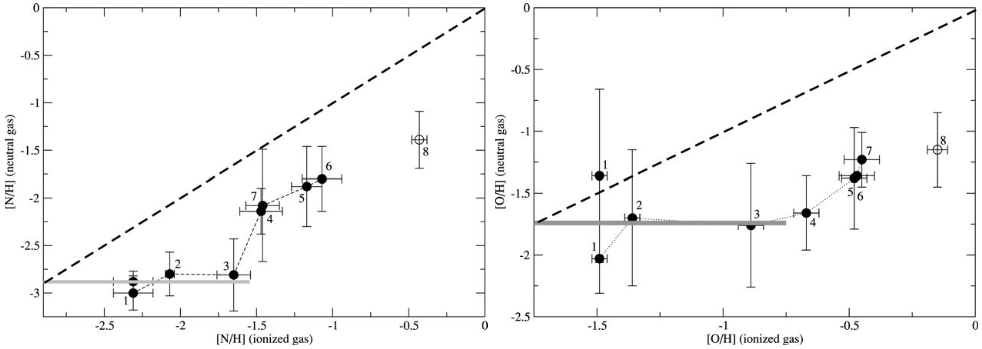

Figure 2. The abundances of nitrogen (left) and oxygen (right) in the ionized gas and in the neutral gas are compared. Labels: (1) IZw18, (2) SBS0335-052, (3) IZw36, (4) Mark 59, (5) Pox 36, (6) NGC 625, (7) NGC 1705, (8) NGC 604/M33. The dashed line indicates the 1:1 ratio.

At low-metallicities ($\lesssim 1/8\,Z_\odot$), there may be a plateau for which abundances in the neutral gas are not correlated with those in the ionized gas. The BCDs in this plateau are IZw18, SBS0335-052, and IZw36. There is a strong need for analyzing BCDs with similar metallicities to better characterize the plateau. The enrichment associated with this plateau cannot be due to population III stars but rather by multiple starburst episodes.

At higher metallicities $\gtrsim 1/5\,Z_\odot$, the abundances of the neutral gas and ionized gas are correlated. The global offset is around ~ 0.9 dex, i.e., almost a factor 10. This offset applies to objects with metallicities as large as solar. Moreover, it seems to apply also in the neutral gas of spiral galaxies (M 33/NGC 604; Lebouteiller *et al.* 2006) and not only to BCDs. We might be seeing here the effect of delayed enrichment of metals in the neutral gas.

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