SF2A 2014
J. Ballet, F. Bournaud, F. Martins, R. Monier and C. Reylé (eds)

PROBING GAS FLOWS AROUND GALAXIES WITH SINFONI

C. Peroux[1]

Abstract. The circumgalactic medium (CGM) of typical galaxies is crucial to our understanding of the cycling of gas into, through and out of galaxies. One way to probe the CGM is to study gas around galaxies detected via the absorption lines they produce in the spectra of background quasars. We present high-resolution SINFONI 3D observations of galaxies responsible for high-N HI quasar absorbers. These data allow to determine in details the kinematics of the objects. In addition, we use several indicators to determine the direction of the gas flows in and out of these galaxies. We also compare the gas-phase and stellar metallicities to constrain the star formation history of these galaxies based on VLT/X-Shooter observations. This allows us to compare the neutral and ionised phase metallicities in the same objects and relates these measures to possible signature of low-metallicity gas accretion or outflows of gas enriched by star formation.

Keywords: quasars: absorption lines, Galaxies: kinematics and dynamics, intergalactic medium

1 Introduction

Tremendous progress has been made over the last decade in establishing a broad cosmological framework in which galaxies and large-scale structure develop hierarchically over time, as a result of gravitational instability of material dominated by dark matter (e.g. Springel & Hernquist 2003). A picture arises where galaxy formation is fed by inflows of gas from the inter-galactic medium - IGM (e.g. Keres et al. 2005), counteracted by strong galactic winds (e.g. Oppenheimer et al. 2010), which in concert establish the growth rate of gas and stars within galaxies at all cosmic epochs. These processes can be collectively described as a 'baryon cycle'.

The next challenge is this field is to establish a direct comparison between observations and theoretical predictions. Outflows are ubiquitous in galaxies at various redshifts (e.g. Steidel et al. 2010). However, given the unknown in the ionisation state and number of phases in the gas, it is at present very difficult to measure the mass in these outflows (e.g. Genzel et al. 2010). Moreover, galaxies with the IGM by pervading it with ionising photons, by polluting it with heavy elements formed in stars and supernovae through these supersonic galactic winds. Observations of galaxies in absorption in the spectrum of a background quasar, the so-called quasar absorbers, indicate the presence of metals down to low over-densities at all redshifts (Tumlinson et al. 2011) which, in various models, is interpreted as a signature of strong galactic outflows (Oppenheimer & Davé 2006).

The observational evidence for inflows are even more challenging and just a handful of claims have been reported so far (Bouché, et al. 2013). However, accretion is required to explain some of the basic observed properties of galaxies including the gas-phase metallicity (e.g. Erb et al. 2006) and the cosmological evolution of neutral gas mass (Zafar et al. 2013b). The circum-galactic medium (CGM), broadly defined as the interface between galaxies and the IGM (Shull 2014), is at the heart of these physical processes. The baryon cycle of gas travelling into, through, and out of galaxies is taken place in this CGM.

2 The SINFONI Integral Field Spectroscopy Sample for Galaxy Counterpart to Damped Lyman-α Systems

A way to study the detailed processes at play in the CGM is to bring together, in a unified picture, data on cold gas (<100,000 K), metals and stellar content of the same galaxies. Indeed, the gas from the diffuse medium

[1] Aix Marseille Universit, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388, Marseille, France

surrounding galaxies, is detected via the absorption lines it produces in the spectra of background quasars, and provides a powerful tool to study the CGM of galaxies (Stewart et al. 2011; Stinson et al. 2012). Samples of the strongest of these quasar absorbers, the so-called Damped Lyman-α systems (DLAs), now amount to several hundreds (Prochaska et al. 2005; Noterdaeme et al. 2009; Noterdaeme et al. 2012; York et al. in prep) and the number of known sub-Damped Lyman-α systems (sub-DLAs; Péroux et al. 2003) is also growing (Zafar et al. 2013a). These HI-selected sight-lines offer the prospect to study the direct surroundings of intermediate-redshift galaxies in the few cases where the absorbing-galaxy has been identified.

With the aim of studying the flows of gas in and out of galaxies, we have taken advantage of the 3D spectroscopy at near-IR wavelengths made possible by SINFONI on VLT to successfully detect the galaxies responsible for quasar absorbers (see Fig. 1 for an example). We have been able to detect five high-N(HI) absorbing-galaxies out of 16 searched for at $z \simeq 1$–2. In these studies, using SINFONI data at a resolution of 0.8-arcsec (∼6 kpc at z∼1), we identified galaxy counterparts for the absorbers and estimated star formation rates and emission metallicities from emission line detections. We also acquired X-Shooter emission-line spectra covering the observed wavelength 300 nm to 2.5 μm for these absorbing-galaxies (see Fig. 2). The slit was oriented to obtain a spectrum of both the background quasar and the galaxy responsible for the high-N(HI) quasar absorber. These data thus allow for a robust estimate of HII abundance in these and allow for a comparison of the metallicities in the neutral and ionised phase of the same objects.

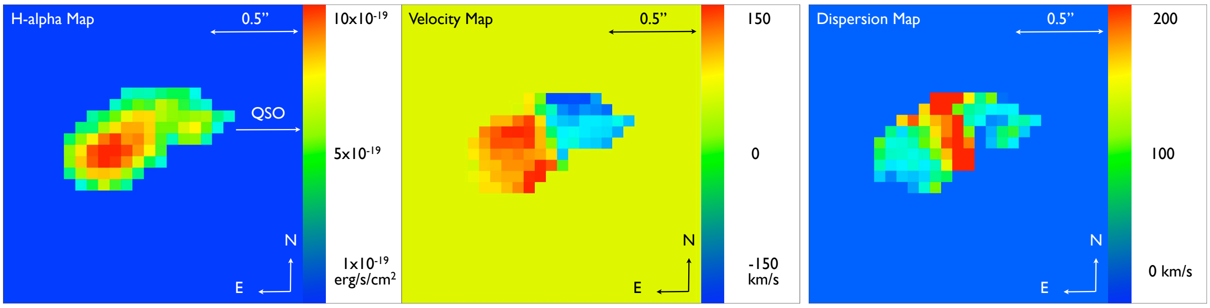

Fig. 1. H-α flux map, H-α velocity field and H-α velocity dispersion maps of the sub-DLA-galaxy towards Q2352-0028, zabs=1.0318. The velocity map indicates a strong gradient as expected from a rotating disc (Péroux et al. 2013).

3 Results

The SINFONI data are used to measure the dynamical masses of the systems which are found to range from $10^{9.8}$ to $10^{10.9}$ $M_\odot$. The mass of gas, however, is found to be between $10^{8.8}$ to $10^{9.7}$ $M_\odot$. We note that whenever the halo masses have been derived, these are significantly larger than the gas masses. Moreover, for the rotating galaxies, we are able to estimate the mass of the halo in which the absorbers reside assuming the systems are virialised. We find large values ranging from $10^{11.8}$ to $10^{12.8}$ $M_\odot$. These halo masses are an order of magnitude larger than the one derived by Pontzen et al. (2008) based on dedicated Smoothed-Particle Hydrodynamics (SPH) simulations. In fact, these authors predict that the major contributors to the population of DLAs are haloes of masses 10^9<$M_{\rm halo}$<10^{11} $M_\odot$, with a peak at $M_{\rm halo}$=10^{10} $M_\odot$. It is possible that the 5 high-N(HI) absorbers we have detected amongst 16 searched for are thus the high mass end of the DLA distribution.

In addition, our measurements of the absorbing-galaxy cross-section and $M_{\rm halo}$ imply that the systems have halo masses 4 to 5 orders of magnitude larger or cross-sections 3 orders of magnitude smaller than required to lie on the relation predicted by Pontzen et al. (2008). In fact, these authors note that their estimate of the cross-sections are larger than in previous simulations (Gardner et al. 1997; Nagamine et al. 2004) and suggest that this might be due to their particular feedback implementation. While the systems observed here are relatively metal-rich and hence expected to have (or have had) large SFR, the detection rate of our sample indicates that theses are representative of more than just a few percent of the DLA population. In two of the cases, additional HST imaging allows to determine the stellar mass of the absorbing-galaxies. These are derived to be $10^{9.5}$ to $10^{9.3}$ $M_\odot$, respectively (see Krogager et al. 2013; Christensen et al. 2014). These measurements allow for a direct test of the mass-metallicity relation in quasar absorbers claimed by several authors (Ledoux et al. 2006; Möller et al. 2013; Christensen et al. 2014).

Our results based on X-Shooter data suggest that the abundances derived in absorption along the line-of-sight to background quasars are a reliable measures of the overall galaxy metallicities (Péroux et al. 2014). The 2D metallicity maps based on SINFONI observations show small negative metallicity gradients. The flat slopes are in line with the differences observed between the two phases of the gas. These results suggest that a comparison of the HI and HII metallicities is a robust indicator of the internal gradients. In addition, we use several indicators to measure the quantity of dust in the ionised and neutral phases of these systems. The presence of dust in the HI phase can be estimated from the observed depletion of refractory elements. We find measures from the Balmer decrement of the galaxies to be in line with values derived from element ratios in the HI gas.

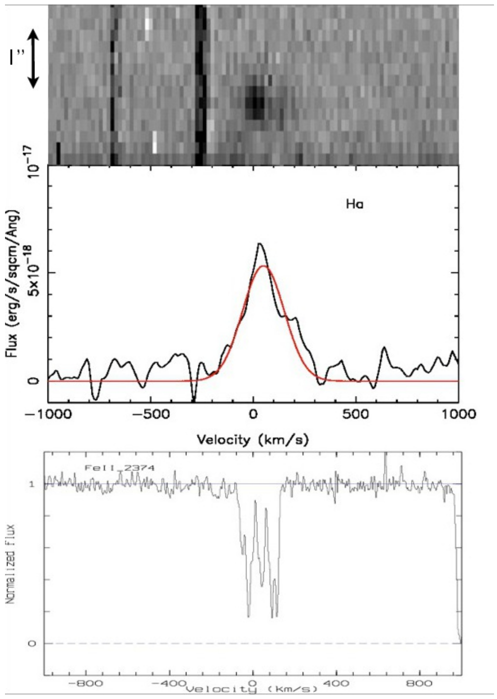

Fig. 2. Emission and absorption lines in the sub-DLA towards Q2352-0028. The black streaks in the 2D image are sky lines. The range of velocities spread by both the emission and the absorption profiles are comparable (Péroux et al. 2014).

4 Conclusions

We further use several indicators to study the flow of gas around these absorbing-galaxies. Indeed, the observations presented here allow to combine various tests which, together, can put constrains on the directions of the flows around z∼1 or 2 galaxies. Based on arguments on the star formation per unit area, we argue that all systems might produce winds. In all five cases, we measure EW(MgII λ 2796) $>$ 1Å at the position of these absorbers and find that the saturated profiles extend both sides of the galaxies systemic redshifts, which are believed to be signatures of winds. Using a comparison of the emission and absorption kinematics, as well as inclination and orientation arguments, we find that two of the systems show signature of an outflow in the velocity profile. For the remaining three systems, it is difficult to reach definitive conclusions. In particular, there are two cases where the presence of two separate objects detected in HST and SINFONI imaging complicate the interpretation. Finally, 2D abundance maps and measure of the metallicity gradients in three of the five systems do not indicate signatures expected from infall of fresh gas onto the galaxies. Overall, our data are therefore consistent with the gas seen in absorption being due to material co-rotating with the halo of their discs although some lines of evidence might support the presence of outflows traced in absorption. In two cases, we have the strongest evidence for the presence of outflows. This is also supported by a large value of star formation rate per unit area, $\Sigma_{\rm SFR}$.

This work has benefited from support of the 'Agence Nationale de la Recherche' with reference ANR-08-BLAN-0316-01.

References

Bouché, N., Murphy, M. T., Kacprzak, G. G., Péroux, C., Contini, T., Martin, C. & Dessauges-Zavadsky, M., 2013, Nature, 341, 40

Christensen, L.; Moller, P.; Fynbo, J. P. U. & Zafar, T., 2014, MNRAS, 445, 225

Erb, D. K., Shapley, A. E., Pettini, M., Steidel, C. C., Reddy, N. A. & Adelberger, K. L., 2006, ApJ, 644, 813

Gardner, J. P., Katz, N., Weinberg, D. H. & Hernquist, L., 1997, ApJ, 486, 42

Genzel, R., et al., 2010, MNRAS, 407, 2091

Keres, D., Katz, N., Weinberg, D. H. & Davé, R., 2005, MNRAS, 363, 2

Krogager, J-H, Fynbo, J., Ledoux, C., Christensen, L., Gallazzi, A., Laursen, P., Möller, P., Noterdaeme, P., Péroux, C., Pettini, M., Vestergaard, M., 2013, MNRAS, 433, 309

Ledoux, C., Petitjean, P., Fynbo, J. P. U., Möller, P. & Srianand, R., 2006, A&A, 457, 71

Möller, P., Fynbo, J. P. U., Ledoux, C. & Nilsson, K. K., 2013, MNRAS, 430, 2680

Nagamine, K., Springel, V. & Hernquist, L., 2004, MNRAS, 348, 421

Noterdaeme, P., Petitjean, P., Ledoux, C. & Srianand, R., 2009, A&A, 505, 1087

Noterdaeme, P., et al., 2012, A&A, 547L, 1

Oppenheimer, B. D. & Davé, R., 2006, MNRAS, 373, 1265

Oppenheimer, B. D.; Davé, R., Keres, D., Fardal, M., Katz, N., Kollmeier, J. A. & Weinberg, D. H., 2010, MNRAS, 406, 2325

Péroux, C., Dessauges-Zavadsky, M., D'Odorico, S., Kim,T. S., & McMahon, R., 2003, MNRAS, 345, 480.

Péroux, C., Bouché, N., Kulkarni, V. P. & York, D. G., 2013, MNRAS, 436, 2650

Péroux, C., Kulkarni, V. P. & York, D. G., 2014, MNRAS, 437, 3144

Pontzen, A., Governato, F., Pettini, M., Booth, C. M., Stinson, G., Wadsley, J., Brooks, A., Quinn, T. & Haehnelt, M., 2008, MNRAS, 390, 1349

Prochaska, J. X., Herbert-Fort, S. & Wolfe, A. M., 2005, ApJ, 635, 123

Shull, J. M., 2014, ApJ, 784, 142

Springel, V. & Hernquist, L., 2003, MNRAS, 339, 289

Steidel, C. C., et al., 2010, ApJ, 717, 289

Stewart, K. R., Kaufmann, T., Bullock, J. S., Barton, E. J., Maller, A. H., Diemand, J. & Wadsley, J., 2011, ApJ, 738, 39

Stinson, G., S., et al., 2012, MNRAS, 425, 1270

Tumlinson, J. et al., 2011, Science, 334, 948

Zafar, T., Péroux, C., Popping, A., Deharveng, J.-M., Milliard, B. & Frank, S., 2013b, A&A, 556, 141

Zafar, T., Popping, A. & Péroux, C., 2013a, A&A, 556, 140