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Multi-line Diagnostics of the Interstellar Medium

CH^+(1-0) in a z∼2.8 galaxy group: Probe of multi-phasic turbulent gas reservoirs

Alba Vidal-García[1,*], *Edith* Falgarone[1,**], *Fabrizio* Arrigoni Battaia[2], *Benjamin* Godard[1], *Rob J.* Ivison[3], *Martin A.* Zwaan[3], *Cinthya* Herrera[4], *David* Frayer[5], *Paola* Andreani[3], *Quong* Li[6], *Raphaël* Gavazzi[7], *Edwin* Bergin[8], *Fabian* Walter[9], and *Alain* Omont[7]

[1]LPENS, Université PSL, CNRS, Sorbonne Université, Université de Paris, Paris, France
[2]Max Planck Institute fur Astronomie, Garching, Germany
[3]European Southern Observatory, Garching, Germany
[4]Institut de radioastronomie millimétrique, Saint Martin d'Hères, France
[5]Green Bank Observatory, Green Bank, WV, USA
[6]Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, People's Republic of China
[7]Sorbonne Université, CNRS, Institut d'Astrophysique de Paris, Paris, France
[8]University of Michigan, Ann Arbor, MI, USA
[9]Max Planck Institute fur Astronomie, Heidelberg, Germany

Abstract. Starburst galaxies at redshifts z∼2 to 4 are among the most intensely star-forming galaxies in the universe. The way they accrete their gas to form stars at such high rates is still a controversial issue. We have detected the CH^+(1-0) line in emission and/or in absorption in all the gravitationally lensed starburst galaxies observed so far with ALMA in this redshift range. The unique spectroscopic and chemical properties of CH^+ allow its rotational transition to highlight the sites of dissipation of mechanical energy. Whilst the absorption lines reveal highly turbulent reservoirs of low-density molecular gas extending far out of the galaxies, the broad emission lines with widths up to a few thousands of km/s, arise in myriad molecular shocks powered by the feedback of star formation and possibly active galactic nuclei. The CH^+(1-0) lines therefore probe the sites of prodigious energy releases, mainly stored in turbulent reservoirs before being radiated away. These turbulent reservoirs act as extended buffers of mass and energy over timescales of a few tens to hundreds of Myr. Their mass supply involves multi-phasic gas inflows from galaxy mergers and/or cold stream accretion, as supported by Keck/KCWI Lyα observations of one of these starburst galaxies.

1 Introduction

In numerical simulations, galaxies grow by accreting cold streams [1]. The momentum exchange between the streams and the galaxies at the bottom of the dark matter potential well is so violent that a large turbulent region is created in the circumgalactic medium (CGM) around the galaxies. While the feedback from Active Galactic Nuclei (AGN) and star formation is

*e-mail: alba.vidal@ens.fr
**e-mail: edith.falgarone@ens.fr

observed through powerful outflows [2], cold stream accretion is still elusive. Such large turbulent reservoirs of diffuse gas around galaxies are therefore signposts of cold stream accretion. Accretion of diffuse matter onto galaxies is traced by redshifted absorption lines. The CH^+ molecule has been a valuable tracer of the CGM motions around high-redshift lensed starburst galaxies [3].

CH^+ is a most fragile but precious molecular tracer. It has a high endothermic formation (E_{form} ∼0.5eV) and is highly reactive, so it is observed where it forms. Once formed, its lifetime is so short (∼1 year), that a warm chemistry activated by bursts of turbulent dissipation is needed to overcome its destruction rate. Unlike most molecules, CH^+ is not photodissociated, but destroyed by collisions. Finally, it has a high dipole moment, so absorption lines of its J=1-0 transition trace diffuse gas and emission lines trace high density gas seen in shocks and photodissociation regions [4, 5]. All these properties make CH^+ a unique tracer of dissipation of mechanical energy in turbulence [3, 6].

2 SMM J02399-0136 galaxy group

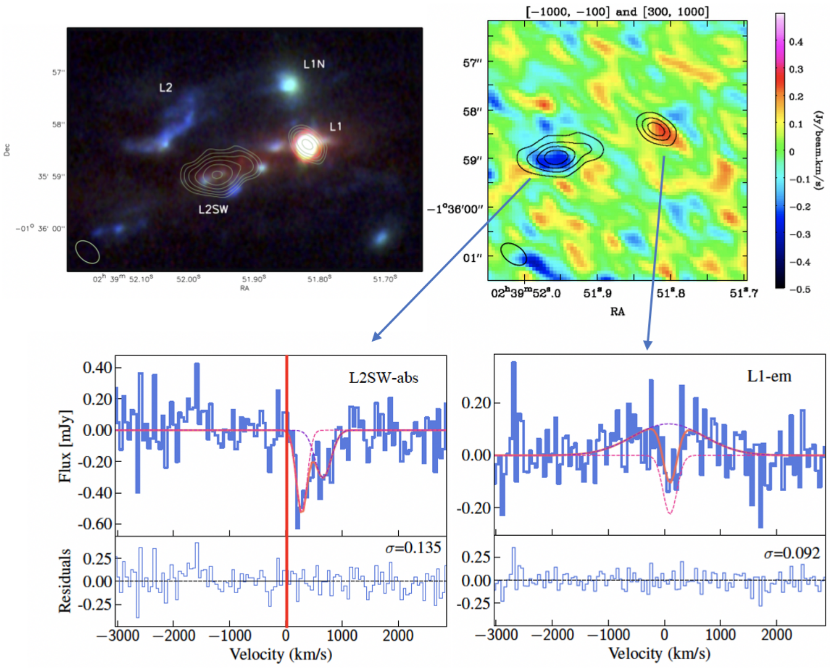

Figure 1: *Upper row: Left:* ALMA rest-frame 360-μm continuum image of SMM J02399−0136 over a false-colour composite from Frontier Fields *HST* frames. *Right:* Map of the CH^+ line integrated area (i.e. moment-0) over the velocity range [-1000,-100] and [300,1000] km s^{-1}. *Lower row:* Two CH^+(1-0) continuum-subtracted ALMA spectra, the residuals and the r.m.s noise level are also shown. The dashed lines show individual Gaussian fits to the emission and absorption components. The spectra are obtained over the L2SW continuum peak (*left*), and over a solid angle of ∼ 1 arcsec^2 south-west of L1 (*right*).

We have observed and detected the J=1-0 transition of CH^+ in 18 starburst galaxies at z≃2-3. One of the targets is SMM J02399−0136, a galaxy group lensed by the Abell 370 cluster [7]. The group comprises a starburst galaxy, L2SW, and an AGN, L1, shown in the continuum observations of the top panels of Fig. 1 and two reflection nebulae unseen in the sub-milimeter. The average redshift of the two galaxies, $z_{\rm ref} = 2.8041 \pm 0.0004$, inferred from the ALMA CO(7-6) image at a resolution (0.48"×0.46"), is used as a reference for the velocity scale [6]. The spectra towards L2SW and L1 show broad lines of widths of ~600 and ~300 $\rm km\,s^{-1}$ respectively for CH^+. The absorption line against L2SW is redshifted by $\sim$ 600 $\rm km\,s^{-1}$, and therefore traces inflowing gas towards the galaxy. From the linewidth, we estimate the radius of the turbulent CGM to be ~20 kpc (see [6] for the details of the calculation), which corresponds to the integral scale of the CGM turbulence assuming that the width of the line is only due to turbulence. The line opacity provides the column density of CH^+ $N(CH^+) \sim 6 \times 10^{14}\,\rm cm^{-2}$ and from these observables we derive the mass of the turbulent CGM to be $\sim 4 \times 10^{10}\,M_\odot$.

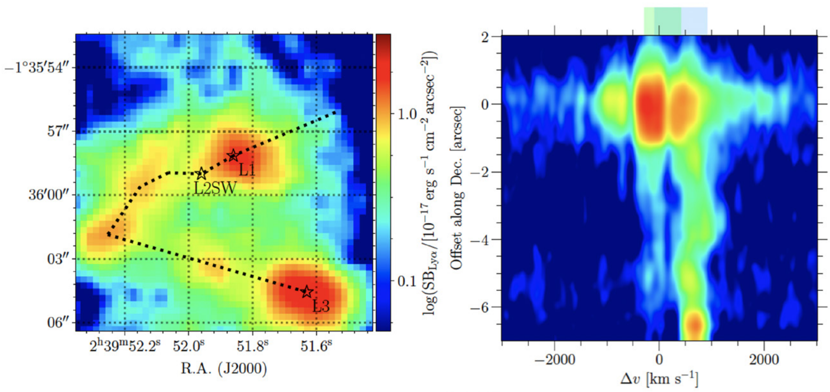

Figure 2: Position-velocity map of the Lyα nebula on the *right* taken along the track shown in the *left* panel (black dots). The blue and green boxes at the top show the full velocity coverage of the CH^+ absorption lines in front of L2SW and L1, respectively.

The Lyα observations obtained with Keck/KCWI of this galaxy group are presented in [8]. The brightest part is concentrated around the starburst and AGN but the faintest parts extend to regions up to over 80 kpc. Fig. 2 shows a position-velocity map of the Lyα emission across the nebula. The cut shows that the brightest parts are also those with the largest widths, with FWZI up to $\sim$ 6000 $\rm km\,s^{-1}$. In contrast, in the most extended parts, lines are much narrower (FWHM~400 $\rm km\,s^{-1}$) and appear redshifted by $\sim$ 600 $\rm km\,s^{-1}$, similarly to the CH^+ absorption lines which are indicated by the shaded boxes.

3 What we learn from the comparison of Lyα and CH^+ observations

In the left panel of Fig. 3, the agreement of the size of the turbulent reservoir of diffuse molecular gas seen in CH^+(1-0) absorption against the L2SW and L1 and that of the Lyα nebula not only validates the assumptions made to calculate the CGM radius but also suggests that the CGM is at least biphasic, with a cool molecular phase of low density that we detect in CH^+(1-0) absorption and a warmer phase emitting in Lyα. Note that the lensing shear direction makes the kpc/arcsec correspondence different along the RA and Dec axis.

The Lyα spectra in the direction of L1, L2, L2SW and L3 are shown in the right panel of Fig. 3. The line profiles are asymmetric and different at each positions. The blue and green

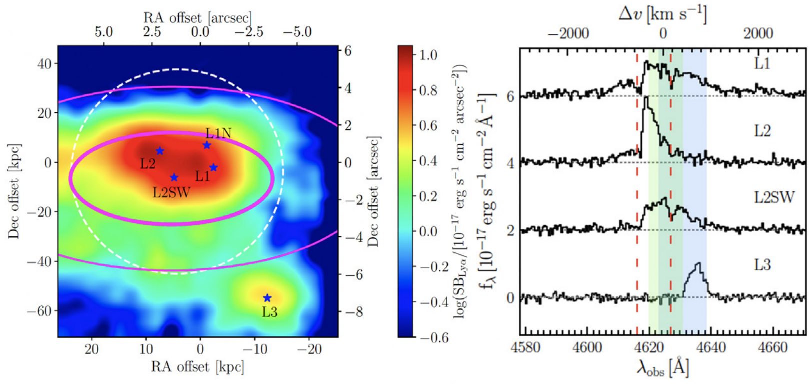

Figure 3: *Left:* Continuum-subtracted Lyα emission of the gas surrounding SMM J02399−0136. The two magenta ellipses show the size of the turbulent reservoir traced by CH^+(1-0) absorption, derived for two durations of the starburst phase, 50Myr (thick) and 100Myr (thick). *Right:* Lyα spectra observed in the direction of L1, L2, L2SW and L3. The blue and green shaded regions mark the velocities of the CH^+(1-0) absorption lines towards L2SW and L1.

shaded boxes show that the velocity range of the CH^+(1-0) absorption lines covers the red wing of the Lyα emission at these positions and the velocity range of the extended emission. The agreement of the velocity of the CH^+ absorbing gas and the extended Lyα emission means that both phases are dynamically coupled and inflowing towards the galaxies. This redshifted gas scatters photons back from the observer and contributes to the asymmetry of the Lyα line profiles. From these comparisons and a large set of multi-transition CO ancillary data [6], we conclude that the 20 kpc-scale CGM in SMM J02399−0136 is multi-phasic and inflowing towards the galaxies.

Several kpc-scale shocks are detected tentatively in CH^+(1-0) emission in the environment of the starburst galaxy and AGN [6]. Their specific location in space and velocity with respect to the high-velocity Lyα emission suggests that they lie at the interface of the inflowing CGM and the high-velocity Lyα emission, and signpost the feeding of CGM turbulence by AGN- and stellar-driven outflows. The mass and energy budgets of the CGM require net mass accretion at a rate commensurate with the star formation rate. From this similarity, we infer that the merger-driven burst of star formation in this galaxy group is ultimately fuelled by large-scale gas accretion.

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