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A molecular scan in the Hubble Deep Field North

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Abstract. Our understanding of galaxy evolution has traditionally been driven by pre-selection of galaxies based on their broad-band continuum emission. This approach is potentially biased, in particular against gas-rich systems at high-redshift which may be dust-obscured. To overcome this limitation, we have recently concluded a blind CO survey at 3mm in a region of the Hubble Deep Field North using the IRAM Plateau de Bure Interferometer. Our study resulted in 1) the discovery of the redshift of the bright SMG HDF850.1 ($z = 5.183$); 2) the discovery of a bright line identified as CO(2-1) arising from a BzK galaxy at $z = 1.785$, and of other 6 CO lines associated with various galaxies in the field; 3) the detection of a few lines (presumably CO(3-2) at $z \sim 2$) with no optical/NIR/MIR counterparts. These observational results allowed us to expand the parameter space of galaxy properties probed so far in high-z molecular gas studies. Most importantly, we could set first direct constraints on the cosmic evolution of the molecular gas content of the universe. The present study represents a first, fundamental step towards an unbiased census of molecular gas in 'normal' galaxies at high-z, a crucial goal of extragalactic astronomy in the ALMA era.

Keywords. galaxies: evolution - galaxies: ISM - ISM: evolution

1. Introduction

Most of our current understanding of the formation of galaxies is based on blank optical and near-IR deep observations of their stellar continua, and to less extent of their ionized gas and the dust continuum emission: The luminosities and colors of stellar continua are used to identify high-z galaxies and to gauge their stellar contents and star formation rates (e.g., Steidel *et al.* 2004; Le Fèvre *et al.* 2005; Lilly *et al.* 2007). Narrow-band observations unveiled the presence of a population of star-forming galaxies with bright line emission arising from the ionized gas, but faint stellar continua (e.g., Ouchi *et al.* 2009, 2010). Wide field observations of the dust continuum gauge the obscured component of the star formation process (see review by Casey *et al.* 2014). The observational milestone resulting from all these investigations is the 'Lilly–Madau' plot, which traces the evolution of star formation rate (SFR) density in the universe as a function of cosmic time. These searches targeted star formation processes in act (through photoionized gas tracers or dust emission) or in the past (through stellar masses and ages). On the other hand, observations of the molecular gas, which is the fuel for star formation, have been limited to follow–up studies of galaxies that have been pre–selected from optical/NIR deep surveys, or to rare, extreme sources like bright sub-mm galaxies. Color–selection techniques (e.g., BzK, BMBX) have revealed significant samples of gas–rich, star forming galaxies at $z = 1.5$ to 2.5 ($M_{\mathrm{H}_2} = 10^{11}$ M$_\odot$, $M_* = 10^{10}$ M$_\odot$, SFR = 100 M$_\odot$ yr^{-1}, Daddi *et al.* 2008, 2010a,b; Greve *et al.* 2010; Tacconi *et al.* 2010, 2013; Genzel *et al.* 2010, 2011, 2014;

Decarli *et al.* 2014a). However, optical/NIR selections are likely missing gas-dominated and/or obscured galaxies, especially at intermediate to high redshift.

2. A molecular scan in the HDF-N

In order to overcome this limitation, we performed a volume–limited census of the molecular gas content in primeval galaxies, through a blind CO search over a large part of the 3mm transparent window of the atmosphere (79–115 GHz). The pointing center (RA=12:36:50.300, Dec=+62:12:25.00, J2000.0) was chosen to include the bright sub-mm galaxy HDF850.1 (Hughes *et al.* 1998). The primary beam was $41''$–$60''$ in diameter. The typical beam size in our molecular line scan is $3'' \times 2.7''$ ($\sim$25 kpc at $z = 2$, and roughly constant at any $z \gtrsim 1$). The final cubes have a typical rms of 0.3 mJy beam^{-1} in 90 km s^{-1} channels, or $L'_{\rm lim} = (4-8) \times 10^9$ K km s^{-1} pc^2, assuming a typical line width of 300 km s^{-1}, and by requiring a 3.5-σ line detection (see Decarli *et al.* 2014b).

Our collapsed cube resulted in the deepest 3mm continuum map available to date, with a 1-σ rms of 8.5 μJy beam^{-1} (Decarli *et al.* 2014b). More importantly, we discovered various CO lines:

i- We observed 2 lines arising from the bright sub-mm galaxy HDF850.1. We identified them as CO(5-4) and CO(6-5), which placed the source at z=5.183, as confirmed by follow-up observations of the CO(2-1) and [CII] lines (Walter *et al.* 2012; Neri *et al.* 2014). This was the first spectroscopic redshift measurement for this iconic source (14 years after its discovery by Hughes *et al.* 1998).

ii- We discovered 7 CO lines spatially associated with optical/NIR counterparts. One of these galaxies is a massive ($M_* = 2.5 \times 10^{11}$ M$_\odot$) star-forming (38 M$_\odot$ yr^{-1}) BzK galaxy at z=1.784. A similarly bright CO line, on the other hand, is associated with a galaxy with $\sim$1 order of magnitude smaller stellar mass at z=2.044 (Decarli *et al.* 2014b). This example shows that large molecular gas reservoirs can be found in galaxies with very different properties at $z \sim 2$ (Decarli *et al.* 2014b; Walter *et al.* 2014).

iii- Other line candidates were found in a spatial position which shows absolutely no optical/NIR/MIR counterparts, despite the exquisite depth of the available ancillary data. The most remarkable example, dubbed ID.18, has a flux of 0.58 ± 0.11 Jy km s^{-1} and is detected in independent data blocks. It peaks at 112.593 GHz. We argue that the line is CO(3-2) at $z = 2.071$. A second transition, CO(4-3), is tentatively detected (at $\lesssim$4-σ level) at the same position in our 2mm follow-up observations, thus confirming the line identification.

3. CO luminosity functions and molecular gas content

We compare our results with the empirical predictions by Sargent *et al.* (2014) and with semi-analytical cosmological models by Lagos *et al.* (2011) and Obreschkow *et al.* (2009a,b), as well as with the observed CO luminosity function at $z = 0$ as measured by Keres *et al.* (2003). We place our constraints in the following way: We bin the CO blind detections in terms of CO luminosity, and we normalize to the volume of the universe in each redshift interval. For each luminosity bin, we place a lower limit corresponding to our secure detections (i.e., the lines that we managed to confirm via independent follow-up observations) and upper limits that represent the case where all line candidates are in fact real. Our blind detections probe a CO luminosity range close to the 'knee' of the predicted CO luminosity functions (Walter *et al.* 2014).

We convert the CO luminosity functions into a cosmic molecular content, $\rho_{\rm H2}(z)$. This is the amount of molecular gas in galaxies per unit comoving volume. The luminosity

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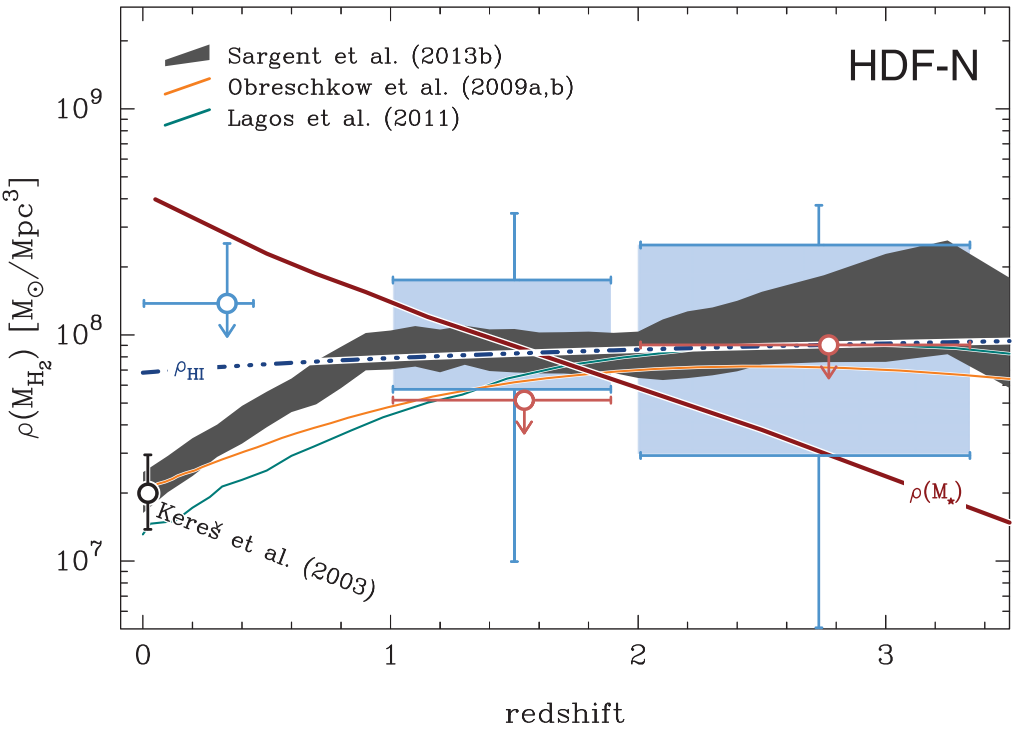

Figure 1. The evolution of the cosmic H_2 mass density, $\rho_{H2}(z)$ based on predictions from semi–analytical comological models (Obreschkow *et al.* 2009a, 2009b, Lagos *et al.* 2011) as well as the empirical predictions by Sargent *et al.* (2014). The blue–shaded area shows only the contribution of our blind detections to $\rho(M_{H2})$, *not* corrected/extrapolated for a population of undetected sources at lower or higher L'_{CO}, while the limits from the CO stacks over a H-band flux-limited sample of galaxies are shown as red points and arrows. For a comparison, the evolution of the cosmic neutral gas mass density (ρ_{HI}) and of the stellar mass density (ρ_*) are also plotted. Figure taken from Walter *et al.* (2014).

functions from empirical predictions or semi-analytical models are converted into H_2 mass via standard Galactic correction factors, and then integrated over the whole L_{CO} range. On the other side, we do not attempt to correct for sources not detected in our scan at both lower and higher L'_{CO} luminosities, given the unknown shape of the luminosity function. A comparison to empirical predictions of $\rho_{H2}(z)$ shows that the securely detected sources in our molecular line scan already provide significant contributions to the predicted $\rho_{H2}(z)$ in the redshift bins $\langle z\rangle \approx 1.5$ and $\langle z\rangle \approx 2.7$. Accounting for galaxies with CO luminosities that are not probed by our observations results in cosmic molecular gas densities $\rho_{H2}(z)$ that are higher than current predictions (see Fig. 1 and Walter *et al.* 2014). We note however that the current uncertainties (in particular the luminosity limits, number of detections, as well as cosmic volume probed) are significant.

4. Conclusions

Our molecular line scan of the HDF-N allows us to place first direct limits on CO luminosity function and on the molecular gas density in 'normal' galaxies at high redshift without any pre-selection based on optical/NIR/MIR wavelength observations. Our data shows that galaxies close to the peak of star formation activity ($z = 1 - 3$) have much higher molecular gas content than galaxies at $z = 0$. This evolution matches or even

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exceeds the one predicted by our current understanding of galaxy properties. We note however that the current uncertainties in our precursor study are significant, and that current models can thus not be ruled out given the available data. The emerging capabilities of the Jansky Very Large Array (JVLA) and of the Atacama Large (Sub–)Millimeter Array (ALMA) will enable similar molecular deep field studies to much deeper levels and larger areas (e.g., da Cunha *et al.* 2013).

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