Discovery of CO absorption at $z = 0.05$ in G0248+430*

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ABSTRACT

Absorption lines in front of distant quasars are quite rare in the millimeter domain. They can, however, bring very useful and complementary information to emission lines. We report here the detection with NOEMA of CO(1–0) and CN(1–0) lines in absorption, and the confirmation of CO emission in the quasar/galaxy pair G0248+430/G0248+430. The system G0248+430 corresponds to two merging galaxies (a Seyfert and a LINER) at $z = 0.0519$ with a tidal tail just on the line of sight to the background quasar G0248+430 at $z = 1.313$. Optical (CalH α), H1 21 cm, and OH-1667 MHz absorption lines associated with the tidal tail of the foreground system have previously been detected toward the quasar, while four CO lines at different rotation $J$ levels have been detected in emission from the foreground galaxies. New H1 21 cm line observations with the upgraded GMRT array are also presented. We discuss the molecular content of the merging galaxies, and the physical conditions in the absorbing interstellar medium of the tidal tail.

Key words. galaxies: active – galaxies: ISM – galaxies: nuclei – quasars: absorption lines – quasars: general

1. Introduction

Most of our knowledge of molecular gas in galaxies at high or low redshift have been obtained through CO emission line studies. However, absorption lines can bring new and complementary information. In contrast to emission, absorption lines remain observable at practically any distance, with the sensitivity only determined by the strength of the background source (e.g., Combes 2008). Given a strong enough continuum source, (≥50 mJy), millimeter-wave absorption lines can be used to obtain information about molecular gas and star formation in "normal" galaxies. While emission lines are sensitive to dense and warm molecular gas, absorption lines may also arise from low-excitation and diffuse gas, which is more prevalent in normal galaxies (e.g., Wiklind & Combes 1995, 1996, 1997; Menten et al. 2008; Henkel et al. 2009; Muller et al. 2014).

Once a galaxy has been detected in the strongest CO absorption lines, deeper studies in other molecular lines allow characterization of the physical and chemical conditions in the absorbing gas (e.g., Henkel et al. 2005; Bottinelli et al. 2009; Muller et al. 2014, 2016; Riquelme et al. 2018). The relative strengths of species like HC3N, where the excitation is dominated by the cosmic microwave background (CMB), can be used to determine the CMB temperature (e.g., Henkel et al. 2009; Muller et al. 2013). Comparisons between the redshifts of different transitions (e.g., NH3, CH3OH, OH) can be used to test for cosmological variations in the fundamental constants (e.g., Uzan 2011; Kanekar 2011; Kanekar et al. 2012; Rahman et al. 2012; Bagdonaite et al. 2013).

In this paper we report the discovery of CO absorption at $z \sim 0.05$, in front of the quasar G0248 at $z = 1.31$ (Kuehr 1977). The absorption comes from a foreground pair of galaxies called G0248 (Junkkarinen 1987), consisting of the two sources G1 and G2. A tidal tail connects, in projection, G2 with the background quasar. Optical absorption lines (CaII and NaI) have been detected at the G0248 redshift $z = 0.0519$, or very close (0.05146, at ~150 km s$^{-1}$) by Sargent & Steidel (1990) and Womble et al. (1990). They noted that the QSO and the galaxy nuclei are separated by 14.7″ = 14.7 kpc at $z = 0.05$, and the absorption is due to the tidal tail crossing the quasar (see Fig. 1).

Throughout this paper we use the ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. At the redshift of the foreground galaxies, the distance scale is 1 kpc per arcsec.

2. Apparent quasar-galaxy merger association

The associated pair of galaxies G0248 is a violent starburst, according to its IRAS far-IR (FIR) flux density measurements, corresponding to $L_{\text{FIR}} = 4.3 \times 10^{11} L_\odot$, and a star formation rate (SFR) of 74 $M_\odot$ yr$^{-1}$ (see Table 1), and the G1 and G2 nuclei (separated by 3.5″ = 3.5 kpc) both show nonthermal activity (Borgeest et al. 1991; Kollatschny et al. 1991). Indeed, G1 is a LINER and G2 a Seyfert 2, and based on their optical emission line excitation both are located in the AGN region of the Baldwin-Phillips-Terlevich (BPT) diagram (Baldwin et al. 1981), plotting [OIII]/Hβ as a function of [NII]/Hα. We note that the above FIR luminosity is extrapolated between 1 and 500 µm, as in Table 1, while Gupta et al. (2018a) adopt the
Table 1. Properties of the merging system G0248.

| $I_{\text{FIR}}$ ($L_\odot$) | $M_*$ ($M_\odot$) | SFR ($M_\odot$ yr$^{-1}$) | $I_{\text{CO}}$ ($\text{K km s}^{-1}\text{pc}^2$) | $M_{\text{H}_2}$ ($M_\odot$) |
|--------------------------|-----------------|-------------------------|---------------------------------|------------------|
| (1)                      | (2)             | (3)                     | (4)                             | (5)              |
| $4.3 \times 10^{11}$     | $6.5 \times 10^{10}$ | 74                     | $0.4 \times 10^{10}$            | $1.6 \times 10^{10}$ |

**Notes.** (1) Total infrared luminosity derived from IRAS fluxes (Kollatschny et al. 1991). (2) Stellar mass estimated from the $L_{\text{IR}}$ luminosity (Bell & de Jong 2001). (3) Star formation rate estimated using the FIR luminosity with the relation SFR $= L_{\text{FIR}}/(5.8 \times 10^8 L_\odot)$ compiled by Kennicutt (1998). (4) Integrated CO line luminosity estimated from the observed CO(1–0) flux (Downes et al. 1993). (5) Total molecular gas mass estimated assuming a CO-to-H$_2$ conversion factor $\alpha_{\text{CO}} = 4.36 M_\odot (\text{K km s}^{-1}\text{pc}^2)^{-1}$.

However, this is based on a derived integrated optical depth at 21 cm of $\int_{\tau_{21}} d\nu = 0.26 \text{ km s}^{-1}$. Gupta et al. (2018a) reprocessed these archival VLA data, and found $\int_{\tau_{21}} d\nu = 0.43 \pm 0.02 \text{ km s}^{-1}$. The column density of the H$_\text{i}$ gas in front of the quasar is large enough for the absorber to be classified as a damped Ly$\alpha$ system, provided the spin temperature is higher than 300 K and/or the covering factor is less than unity.

The calcium depletion on grains of the absorbing gas is high, indicating that the gas must come from a disk rather than from a halo. The column density of NaI is $6.3 \times 10^{13}$ cm$^{-2}$ (Womble et al. 1990), while the ratio N(CaII)/N(NaI) = 0.2–0.3 is low, similar to or lower than the values ~1 of the Galactic disk. The high NaI suggests that the gas could come from outflowing gas from the starburst or the active nucleus in the tidal tail (Heckman et al. 2000). The absence of H$_\text{I}$ emission in the VLA observations (upper limit at $5\sigma$ of $2.3 \times 10^{22}$ cm$^{-2}$ over 30 km s$^{-1}$) is likely due to the phase transformation of the atomic gas to molecular gas in the starburst, which now contains $M(\text{H}_2) = 1.6 \times 10^{10} M_\odot$, with a standard CO-to-H$_2$ conversion factor, $X(\text{CO}) = 2 \times 10^{20}$ cm$^{-2}$/(K km s$^{-1}$).

3. Observations and data analysis

3.1. IRAM observations

We have mapped G0248 at 109.605 GHz for a total of 13 h (8 h on source) allowing us to spatially resolve the CO(1–0) emission line in the foreground gas, and the continuum emissions from both the foreground merging system and the background quasar.

The phase center was RA(2000) = 02$^h$51$^m$35.1$^s$, Dec(2000) = 43$^\circ$15′14.0″, corresponding to the barycenter of the quasar and the merging system (both are located at ~6.5″ from the phase center). The observations were made with nine antennas using the extended array A-configuration of the NOEMA interferometer (project W17CE, P.I.: Combes). The configuration provided a synthesized beam of 0.94 × 0.67 arcsec (PA = 60°). This allows us to resolve the two merging galaxies, which are separated by 3.5″ = 3.5 kpc. The field of view at half power is 47″ at this frequency. The observations were carried out during five days (10, 16, 23, 25 February, and 2 March 2018) in very good weather conditions (sewing in the range ~0.1–0.4 arcsec).

We employed the PolyFix correlator in Band 1 (3 mm), which provides 2 × 8 GHz of instantaneous dual-polarization bandwidth. The spectral resolution was 2 MHz (5.4 km s$^{-1}$ at the redshifted CO(1–0) frequency). The bandwidth allowed us to observe the frequency range from 91.9 to 99.7 GHz in LSB (Lower SideBand), and 107.3 to 115.1 GHz in the USB (Upper SideBand). The data reduction was performed using the latest release of the GILDAS package as of May 2018

The data were calibrated using the NOEMA standard pipeline adopting a natural weighting scheme to optimize both sensitivity and resolution. Flagging was required only on the February 10 data, and was minor. The rms noise is 0.3 mJy in 30 km s$^{-1}$ channels for the line and 8 µJy/beam for the continuum.

3.2. uGMRT observations

We used Band−5 (1000–1450 MHz) of the upgraded Giant Metrewave Radio Telescope (uGMRT) to observe the redshifted H$_\text{i}$ 21 cm line toward the quasar. The observations took place on 29 June 2018. The GMRT Software Backend (GSB) was used to

1 https://www.iram.fr/IRAMFR/GILDAS/
configure a baseband bandwidth of 4.17 MHz split into 512 spectral channels (resolution \( \sim 1.8 \text{ km s}^{-1} \)) centered at 1350.8 MHz. During the 7.5 h observing run, 3C48 was observed for flux density scale and bandpass calibrations. The total on-source time was 6.6 h. The data were edited, calibrated, and imaged using the Automated Radio Telescope Imaging Pipeline (ARTIP) that is being developed to perform the end-to-end processing of data from the uGMRT and MeerKAT absorption line surveys (Gupta et al. 2018b; Sharma et al. 2018).

The Stokes I radio continuum image made using the line-free frequency channels and using ROBUST=0.5 visibility weighting (based on Common Astronomy Software Applications, CASA) is shown in Fig. 1. The image has a synthesized beam of 2.49″ × 2.22″ and an rms noise level of 0.45 mJy beam\(^{-1}\). The radio continuum emission associated with Q0248+430 and G1 is unresolved with a deconvolved size <0.2″. The integrated flux densities are 1214 ± 1.3 and 23.7 ± 1.3 mJy, respectively. We extracted the Stokes I 21 cm absorption spectra toward Q0248+430 and G1. The spectral rms noise level in the unsmoothed spectra is 1.2 mJy beam\(^{-1}\). The spectrum of Q0248+430 is presented in Fig. 2. Ninety percent of the total 21 cm optical depth is contained within 49 km s\(^{-1}\) and the total integrated 21 cm optical depth, \( \int \tau dv = 0.53 \pm 0.02 \text{ km s}^{-1} \). In the spectrum of G1 (not shown here), we detect a broad absorption feature \( \sim 100 \text{ km s}^{-1} \) in width centered at 1351.06 MHz. It corresponds to an integrated optical depth of 19 ± 1 km s\(^{-1}\). However, in the different circular polarizations (L for left, R for right) and their cross-correlations, this feature is present only in LL and not in RR; therefore, we consider the feature to be an artifact. For G0248+430 we then use the RR spectrum smoothed to 30 km s\(^{-1}\). Adopting 100 km s\(^{-1}\) as the FWHM of a typical associated 21 cm absorption line (Gupta et al. 2006), we estimate a 3σ 21 cm integrated optical depth limit of 6 km s\(^{-1}\).

### 4. Results

#### 4.1. Implication of CO absorption

The CO(1–0) emission and possible absorption was mapped in the NOEMA field of view of 47 arcsec FWHP around the merging galaxies (G1 and G2 of Fig 1) with 0.94′′ × 0.67′′ resolution. Although the quasar and the tidal tail were only at an angular distance of 6.5′′ from the phase center, the sensitivity was not sufficient to detect molecular emission in the tidal tail. However, in the different circular polarizations (L for left, R for right) and their cross-correlations, this feature is present only in LL and not
The quasar continuum source is unresolved. In the millimeter range, AGN continuum sources are in general restricted to a core smaller than a milliarcsec in size, contrary to the cm emission, extended due to steep spectrum radio lobes (e.g., de Zotti et al. 2010). This size corresponds to 1 pc at the galaxies’ distance, and it is therefore justified to assume that the molecular medium fills the surface of the quasar continuum source. Assuming a filling factor of 1, we can derive the average column density over the beam corresponding to the quasar mm continuum emission and its footprint on the galaxy tidal tail. This will be a lower limit to the actual column density,

\[ N_{\text{tot}} = \frac{8\pi}{c^2} g_J A_J J + 1 \int f(T_s) \, r \, dr, \]  

where \( g_J \) is the statistical weight of level \( J \), \( A_J J + 1 \) is the Einstein coefficient for transition \( J \rightarrow J + 1 \), and the function \( f(T_s) \) is

\[ f(T_s) = \frac{Q(T_s) e^{E_J/kT_s}}{1 - e^{-E_J/kT_s}}, \]  

We adopt the partition function of local thermal equilibrium (LTE), i.e., \( Q(T_s) = \sum g_J e^{-E_J/kT_s} \), where \( E_J \) is the energy of level \( J \) or \( N = J + F \) (for CN) and \( T_s \) is the excitation temperature of the CO or CN molecule. For the CN molecule, we detect the two stronger lines at rest frequencies, 113.488 GHz and 113.490 GHz, which are blended at our spectral resolution (they correspond to \( J = 3/2 - 1/2 \), \( F = 3/2 - 1/2 \), and \( F = 5/2 - 3/2 \)). We do not detect the three other lines, expected to be five times weaker. We have detected CO(1–0) absorption in front of the quasar, with an optical depth \( \tau = 0.016 \) or \( \tau A V = 0.25 \text{ km s}^{-1} \), corresponding to N(CO) = \( 2.9 \times 10^{15} \text{ cm}^{-2} \) or N(H\(_2\)) = \( 2.9 \times 10^{10} \text{ cm}^{-2} \), for a common CO/H\(_2\) abundance ratio of \( 10^{-4} \). For this computation, we have assumed an excitation temperature \( T_s = 15 \text{ K} \). With the same assumptions, the column density of CN is 7.6 \( \times 10^{12} \text{ cm}^{-2} \). The relative abundance of CN/CO = \( 2.6 \times 10^{-3} \) is relatively high for dense clouds, by 1 or 2 orders of magnitude (e.g., Leung et al. 1984), but not necessarily for more diffuse clouds, for which some models predict abundances 100 times higher (Wakelam et al. 2015). The H\(_2\) column density found toward the tidal tail indeed corresponds to that of a diffuse interstellar medium (Welty et al. 2006) (see also Sect. 1).

4.2. Implications of CO emission

Figure 3 displays the NOEMA integrated CO(1–0) emission map and the velocity field of G0248 (zero and first moments of the cube). The central CO(1–0) spectrum is displayed in Fig. 4. For the first time, the CO emission is resolved by our beam of 0.94 \( \times 0.67'' \) and the total extent of the CO emission is \( \sim 4 \text{ kpc} \). The morphology is not symmetric, however, as expected for an interacting galaxy. The velocity field shows clear rotation, with the kinematic major axis in the N–S direction. The projected gradient is relatively low, but this can be explained by the almost face-on orientation (inclination \( \lesssim 30'\)) of both G1 and G2. The systemic velocities of the two galaxies, obtained through their optical spectrum by Kollatschny et al. (1991), are indicated in Fig. 4. They are symmetrically located at \( \pm 80 \text{ km s}^{-1} \) from the center of the absorption, which is at \( z = 0.05151 \). With our high spatial resolution, we can now attribute the CO emission to one or the other galaxy of the pair. The galaxies are separated by \( 3.5'' \) or \( 3.5 \text{ kpc} \), and Hwang & Chiou (2004) find the CO emission centered in the middle of G1 and G2, but they had a synthesized beam of 2\( '' \). As displayed in Table 2, the center of the CO emission coincides clearly with the position of the spiral galaxy G1, and not with the elliptical G2, or with a position in between the two merging galaxies. Within its maximum radial extent of 2 kpc, there is no CO emission detected toward the center of G2. Kollatschny et al. (1991) estimated the V luminosities of both galaxies, \( L_{\text{v}}(\text{G1}) = 4.5 \times 10^{8} L_{\odot} \) and \( L_{\text{v}}(\text{G2}) = 9.4 \times 10^{8} L_{\odot} \). Through kinematical arguments, they also derived a total mass for the ensemble of \( M_{\text{tot}} = 6.7 \times 10^{10} M_{\odot} \). Assuming comparable mass-to-luminosity ratios for the two galaxies, we can estimate the stellar mass of G1 at 2.2 \( \times 10^{10} M_{\odot} \). This estimation is compatible with that obtained from the observed H\(_\alpha\) and [NII] rotation curve: a maximum rotational velocity of 100 km s\(^{-1}\) at a radius of 2 kpc, provided that the inclination of the spiral galaxy G1 is 27\(^\circ\).

The observation of the fundamental CO(1–0) line is the best measure of the total H\(_2\) mass. We compute \( L_{\text{CO}} \), the CO luminosity in units of K km s\(^{-1}\) pc\(^2\), through integrating the CO intensity over the velocity profile, and over the galaxy extent. The total flux is \( S_{\text{CO}}dV = 29 \text{ Jy km s}^{-1} \) (see Table 2) very close to...
Table 3. uGMRT observations of absorption lines.

| Line          | Area  | $V$  | $\Delta V$ | Peak  |
|---------------|-------|------|------------|-------|
|               | km s$^{-1}$ | km s$^{-1}$ | km s$^{-1}$ |       |
| HI          | 0.11±0.01 | −24±1.8 | 33±1.8 | 0.9967 |
| HI          | 0.07±0.01 | −10±1.8 | 8±1.8 | 0.9913 |
| HI          | 0.16±0.01 | −2.6±1.8 | 4.5±1.8 | 0.9664 |
| HI          | 0.17±0.01 | 8.7±1.8 | 12±1.8 | 0.9871 |
| OH          | −0.06±0.01 | −4±2 | 17±5 | 0.9966 |
| OH          | −0.015±0.01 | 14±4 | 8±6 | 0.9982 |

Notes. Area is the integrated optical depth. The $\Delta V$ are FWHM; the peaks correspond to the maximum depth of the signal, as shown in Fig. 2.

4.3. H$\alpha$ absorption

The updated H$\alpha$ 21 cm absorption spectrum toward the quasar is presented in Fig. 2, together with the other absorption lines. We have fitted the spectrum with four Gaussians, and the results are in Table 3. The new H$\alpha$ absorption spectrum with high spectral resolution allows the discovery of quite narrow components (8 km s$^{-1}$, implying a kinetic temperature lower than 1400 K), together with relatively wide wings (33 km s$^{-1}$), although the fit is not unique. Within the errors, the integrated 21 cm optical depth estimated using this spectrum is consistent with that from the VLA spectrum presented in Gupta et al. (2018b). As expected the molecular absorption is coincident with the narrower (implying colder) and stronger 21 cm absorption components at −2.6 and −8.7 km s$^{-1}$. The limited spectral resolution and sensitivity of the molecular data (OH, CO, and CN) does not allow us to carry out a more detailed decomposition. The two main and broader components seen in the H$\alpha$ absorption are only tentatively seen in the OH spectrum, and not in CO or CN. This might be explained by the different sizes of the quasar continuum emission at millimeter and centimeter wavelengths. The radio continuum at 2.3 GHz has an overall extent of 26 mas (27 pc at $z = 0.05$; Fey & Charlot 2000), which is much larger than the size expected at ~100 GHz relevant for CO and CN absorption lines.

4.4. Absorption upper limits

The wide bandwidth of NOEMA allowed us to search for other possible absorptions from lines falling in our frequency range. There is an H$\alpha$CO line at 101.332 GHz; however, the lower level of the transition at 57 K is too high to yield a significant limit. There is CS(2−1) at 97.980 GHz, with a lower level at 2.2 K, and the fundamental O$\beta$ line at 118.750 GHz. These lines were not detected, and we derive 3σ upper limits of N(CS) ≤ 3.3 × 10$^{12}$ cm$^{-2}$ and N(O$\beta$) ≤ 2.9 × 10$^{17}$ cm$^{-2}$, assuming the same excitation temperature of $T_e = 15$ K. The molecular...
oxygen limit is quite high, because the strength of the transition is about 2 orders of magnitude lower than for the CO molecule.

5. Concluding remarks

We reported the discovery of a new CO(1–0) absorption in an intervening galaxy (z = 0.05) in front of a background quasar (z = 1.3). Millimeter molecular absorptions are still very rare at moderate and high redshift: only six systems have been found (e.g., Combes 2008): three are associated-absorbing systems (i.e., from the AGN host itself), one has been detected recently (Allison et al. 2019), and three are intervening absorbers from gravitational lens systems. To date no simple millimeter molecular absorber has been detected in a normal intervening galaxy without strong lensing, and hence more suitable to study variations of fundamental constants. The absorber in front of Q0248 presented here is thus the first one: the absorbing gas is in a tidal tail without any lensing potential.

With high spatial resolution, the number of detections for local millimeter absorption, in the associated-absorption category, is increasing (e.g., Tremblay et al. 2016), providing extremely useful information, for example disentangling inflow from outflow around AGN. Although intervening HI 21 cm absorbers are now more frequent with about a 30% detection rate in case of optically selected sight lines (Gupta et al. 2009, 2013; Dutta et al. 2017), the OH absorbers in intervening galaxies are still rare, with an incidence or a number per unit redshift of nOH ≈ dN OH /dz = 0.008, at z ~ 0.1 (Gupta et al. 2018a).

In the present case, the absorption is from relatively diffuse gas, belonging to a tidal tail at about 17 kpc projected distance from the parent G1 galaxy, the gas-rich spiral from the merging pair. The column density is therefore quite low, and the depth of the absorption rather small, less than 2%. In the near future, the increased sensitivity of ALMA, NOEMA, and large blind surveys with SKA precursors such as MALS (e.g., Gupta et al. 2016; Allison et al. 2016) will make it possible to discover such weak absorbing systems, which was impossible before.

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References

Allison, J. R., Zwaan, M. A., Duchesne, S. W., & Curran, S. J. 2016, MNRAS, 462, 1341
Allison, J. R., Mahony, E. K., Moss, V. A., et al. 2019, MNRAS, 482, 2934