ALMA Observations of Molecular Absorption in the Gravitational Lens PMN0134–0931 at $z = 0.7645$

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Received 2018 April 13; revised 2018 July 13; accepted 2018 July 17; published 2018 August 30

Abstract

We report the detection of molecular absorption lines at $z = 0.7645$ toward the radio-loud quasi-stellar object (QSO) PMN0134–0931. The CO $J = 2–1$ and HCO$^+$ $J = 2–1$ lines are seen in absorption along two different lines of sight to lensed images of the background QSO. The lines of sight are separated by $\sim 0.7645$, corresponding to 5 kpc in the lens plane. PMN0134–0931 represents one out of only five known molecular absorption line systems at cosmologically significant distances. Moreover, it is also one of three such systems where the absorption occurs in a galaxy acting as a gravitational lens. The absorption lines through the two lines of sight are shifted by $215 \pm 8$ km s$^{-1}$, possibly representing rotational motion in one of the lensing galaxies. The absorption profiles are wide, $\sim 200$ km s$^{-1}$, suggesting that the absorption occurs in a highly inclined disk galaxy with a flat rotation curve and a cloud–cloud velocity dispersion $\sim 30$ km s$^{-1}$. Gravitational lens models require two equal mass galaxies to account for the observed configuration of lensed images. The presence of two galaxies in close proximity means that they might be interacting and potentially merging and the kinematics of the molecular gas may not reflect ordered rotational motion. Compared with other high-redshift molecular absorption systems, the column densities of both CO and HCO$^+$ are normal for diffuse molecular gas toward one of the lensed images, but significantly higher toward the other. Also, the abundance ratio $N_{\text{CO}}/N_{\text{HCO}}$ is 2 – 3 times higher than in typical diffuse molecular gas. It is plausible that the second line of sight probes denser molecular gas than what is normally the case for absorption.

Key words: ISM: general – ISM: molecules – galaxies: general – galaxies: high-redshift – quasars: absorption lines

1. Introduction

Molecular absorption lines seen toward flat-spectrum, radio-loud quasi-stellar objects (QSOs) provide an opportunity to study the molecular interstellar medium (ISM) in high-redshift galaxies in much greater detail than what is possible with emission lines. Emission studies of molecular gas in high-redshift galaxies have mostly been carried out using rotational transitions of CO (e.g., Carilli & Walter 2013). Such studies have provided crucial information on the most massive redshifted systems, ultra-luminous, and luminous infrared galaxies, submm galaxies and high-$z$ quasars (e.g., Walter et al. 2003; Daddi et al. 2008; Combes et al. 2011, 2013; Tacconi et al. 2013). However, emission line strengths decrease with the inverse square of the luminosity distance and it becomes increasingly difficult to detect CO emission in high-redshift galaxies.

Absorption lines have the advantage that they remain observable at practically any distance, with the sensitivity determined only by the strength of the background source. Absorption lines can therefore be used to obtain detailed information about the physical conditions in molecular gas in galaxies at any redshift. In addition, while molecular emission studies are sensitive to dense and warm molecular gas, prevalent in actively star-forming galaxies, absorption lines are more likely to arise in the excitationally cold gas, which is prevalent in less-active galaxies. Molecular absorption studies toward background continuum sources thus provide a powerful probe of the evolution of normal galaxies and their ISM (e.g., Wiklind & Combes 1995, 1997; Kanekar & Chengalur 2002; Menten et al. 2008; Henkel et al. 2009; Muller et al. 2014).

Once molecular absorption lines have been detected in a galaxy, deeper studies of accessible molecular lines allow detailed characterization of the physical and chemical conditions in the absorbing gas (e.g., Henkel et al. 2005; Bottinelli et al. 2009; Muller et al. 2011, 2014). The relative strengths of different absorption transitions of species where the excitation is dominated by the cosmic microwave background (CMB), can be used to determine the CMB temperature (e.g., Wiklind & Combes 1997; Noterdaeme et al. 2011; Muller et al. 2013). Comparison between the redshifts of different molecular transitions in an absorber can be used to test for cosmological evolution in the fundamental constants of physics (e.g., Wiklind & Combes 1998; Kanekar 2011; Kanekar et al. 2012, 2015, 2018). Finally, redshifted absorbers provide the opportunity to use ground-based facilities to study molecules whose transitions fall outside atmospheric transparency windows (e.g., molecular oxygen, water vapor, LiH, etc.; Combes & Wiklind 1995, 1997, 1998; Combes et al. 1997; Kanekar & Meier 2015).

The main obstacle to using molecular absorption lines to study molecular gas at high redshift is the scarcity of such systems. Only five molecular absorption line systems at cosmological distances are known. The rarity of these systems is mainly due to the fact that molecular gas is usually found only in the central regions of galaxies, necessitating a small impact parameter with a background continuum source. Hence, molecular absorption is more likely to be found in the host galaxy of an active galactic nuclei (AGN) than in an arbitrary intervening galaxy. Searching for molecular absorption at the AGN redshift ensures a sightline passing through the central region of the host galaxy. In addition, a prior knowledge of the
2. Observations

We observed the CO \( J = 2–1 \) and HCO\(^+\) \( J = 2–1 \) transitions, redshifted into ALMA bands 3 and 4, respectively (hereafter B3 and B4). The observations were done in three separate visits on 2016 September 9 (B4), and September 17 and 19 (B3), under ALMA Cycle 3 project 2015.1.00582.S. The two B3 observations were both done with 40 antennas and PWV\(^4\) \( \sim 0.5 \) and 2.0 mm, respectively. The longest baseline was 3.14 km, resulting in a nominal angular resolution\(^5\) of 0\(\prime\).35. The total on-source time was \( \sim 52 \) minutes. The B4 observations were done with 38 antennas on a single occasion, with PWV\(\sim 0.48 \) mm. The longest baseline was 2.48 km, with a nominal angular resolution of 0\(\prime\).28. The total on-source time for the B4 observation was \( \sim 67 \) minutes.

The correlator setups for our B3 and B4 observations are shown in Table 1. For each band, we used two basebands of width 1.875 GHz and 1920 channels giving a channel separation of 976.563 kHz. With the internal Hanning smoothing applied in the ALMA correlator, the resulting spectral resolution is 1.129 MHz. In the rest frame of the absorber, this corresponds to a velocity resolution of 3.4 km s\(^{-1}\) in B3 and 2.6 km s\(^{-1}\) in B4. This refers to the center of the high-resolution basebands, centered on 101.007 GHz (HCO\(^+\), \( J = 2–1 \)) and 130.276 GHz (CO, \( J = 2–1 \)) in addition, we used two spectral basebands of width 2 GHz with 128 channels in continuum mode. The continuum channels were centered at 90 GHz and 141 GHz, for B3 and B4, each with a combined bandwidth of \( \sim 4 \) GHz, see Table 1. The continuum data was used to construct images of the PMN 0134--0931 system. As these were obtained at different frequency settings than the high spectral resolution basebands, we used continuum levels measured from the high spectral resolution data in the analysis of the absorption lines.

The data reduction and calibration was done with the CASA\(^6\) package following standard procedures. The bright quasar J0006--0623 was used as both bandpass and flux calibrator. The overall flux accuracy is better than \( \lesssim 10\% \) in both B3 and B4. Phase calibration was done with J0141--0928 for both B3 and B4.

In addition to the CO \( J = 2–1 \) and HCO\(^+\) \( J = 2–1 \) transitions, the high spectral resolution observations covered the redshifted transitions of HCN \( J = 2–1 \) (\( \nu_0 = 177.263 \) GHz), HNC \( J = 2–1 \) (\( \nu_0 = 181.325 \) GHz) and H\(_2\)O \( J = 3\)\(_{13} - 2\)\(_{20} \) (\( \nu_0 = 183.310 \) GHz).

3. The Gravitational Lens PMN 0134--0931

The gravitational lens nature of PMN 0134--0931 was discovered independently by Winn et al. (2002) in a survey of

\(^{5}\) The actual angular resolution depends on the uv-weighting applied in the CLEAN process.

\(^{6}\) Common Astronomy Software Applications: http://casa.nrao.edu.
radio continuum sources and by Gregg et al. (2002) in a survey of red QSOs. High-resolution radio continuum observations reveal six compact components with a maximum separation of ~0\"/7 (Winn et al. 2003). The lens itself has not been reliably detected as it is overpowered by the glare of the background, $z_\text{l} = 2.2$ QSO (Gregg et al. 2002; Winn et al. 2003). Five of the six radio components (A–E) have the same spectral index from 1.7 to 43 GHz ($\alpha = -0.69 \pm 0.04$, where $S_\nu \propto \nu^{\alpha}$), while a sixth component (F) has a much steeper spectral index and is only seen in the $\nu_{\text{obs}} \leq 8.4$ GHz radio data. Hence, the F component is likely to arise from a second emission component in the background QSO, physically distinct from the flat-spectrum component. Differential extinction between the lensed QSO images indicates that the lens contains a significant amount of dust (Gregg et al. 2002; Winn et al. 2003) with components C, E, and D + F being more extincted than components A and B. Hall et al. (2002) detected Ca II absorption corresponding to $z = 0.7645$ in a Sloan Digital Sky Survey spectrum, interpreted as originating in the lens.

The large number of image components of PMN 0134–0931 makes it a unique gravitational lens, and it presents a formidable challenge to lens modeling. Keeton & Winn (2003) did a detailed study of this system and concluded that more than one lensing galaxy is needed to account for the five flat-spectrum components. To model the steep spectrum component, a second distinct background source is needed. In their best model, a total of eight lens component is expected, of which six are detected: five images of a flat-spectrum radio core (A–E) and three images of a steep spectrum component (F + two unseen images). The two lensing galaxies, called Gal-N and Gal-S in Keeton & Winn (2003), are of similar mass, with a corresponding velocity dispersion $\sigma \sim 120$ km s$^{-1}$. Gal-N is centered ~0\"/2 south of lens component E and Gal-S is centered ~0\"/15 south of component C. The projected separation of the two galaxies is only 0\"/4 (3.2 kpc at the lens redshift $z_l = 0.7645$). The models suggest that the two galaxies are both oriented in either the east–west direction or the north-south direction, and are highly flattened. The presence of high extinction as well as ionized gas, inferred through scatter broadening of the radio images at low frequencies (Winn et al. 2003), suggests that the lensing galaxies are gas and dust rich and therefore likely to be spiral galaxies.

Absorption of the H I 21 cm line was first detected in the lens of PMN 0134–0931 by Kaneker & Briggs (2003). The 21 cm profile shows two broad components, with the strongest H I component matching the Ca II absorption profile of Hall et al. (2002). The total H I column density is $2.6 \pm 0.3 \times 10^{21}$ cm$^{-2}$, assuming a spin temperature of 200 K and a covering factor of unity. The total velocity coverage of the H I absorption components is $\sim 500$ km s$^{-1}$. Kaneker et al. (2005) searched for HCO$^+$ $J = 2–1$ absorption with the IRAM 30 m telescope, the 6 cm ground state H$_2$CO doublet lines with the GBT and the 2 cm first rotationally excited state of H$_2$CO with both the GBT and the Very Large Array, as well as 18 cm OH absorption toward PMN 0134–0931 using the GBT. While the HCO$^+$ and H$_2$CO lines remained undetected, the two main OH lines at 1665 and 1667 MHz, and the two satellite lines at 1612 and 1720 MHz, were detected. The main OH lines have the same overall shape as the H I 21 cm absorption. The two satellite lines are in conjugate absorption and emission, indicating a high OH column density, and can be used to probe the evolution of fundamental constants over a look-back time of $\sim 6.7$ Gyr (Kaneker et al. 2005).

4. Results

4.1. Millimeter Continuum

Our ALMA continuum images of PMN 0134–0931 are shown in Figure 1. The highest angular resolution (0\"/24 $\times$ 0\"/18) is obtained at 140 GHz using uniform weighting (right panel in Figure 1). This high-resolution continuum image shows the lens components A, B, and C as an extended but not resolved component. The D component is clearly separated from the A–C image by ~0\"/7 and the E component is seen close to the A–C complex. We did not detect the F image which has a steep spectrum and is not likely to contribute to the continuum at millimeter wavelengths. The locations and derived parameters of the continuum components are listed in Table 2 and a comparison with the location of radio continuum images from Winn et al. (2003) is shown in Figure 2. The average spectral index is $\alpha = -1.6$ ($S_\nu \propto \nu^{-1.6}$), which is steeper than at radio wavelengths. This suggests that dust emission from the background source provides a negligible contribution to the rest-frame submm continuum. The 140 GHz observations probe the rest-frame 670 \( \mu \)m emission from the background QSO and if it had a detectable dust continuum this should make the measured spectral index flatter.

The high angular resolution continuum image is compared with the gravitational lens components in Figure 2. The location and relative flux levels are taken from Winn et al. (2003). We assume that the D component is co-located with the second brightest millimeter continuum region. The other lens components line up very well with the rest of the mm continuum emission. The A, B and C components are not resolved but the mm continuum is extended, consistent with three blended sources, dominated by the A component. The flux ratios should be the same as at low radio frequencies, as long as differential lensing does not affect the measured fluxes. Differential lensing could be present if the emission regions of long wavelength radio continuum do not coincide with the millimeter continuum in the background source. The flux ratio between the D and E components is $1.7 \pm 0.4$ at 140 GHz and $2.2 \pm 0.2$ at 15 GHz (Winn et al. 2003). The error of the mm continuum flux ratio takes a 10% absolute calibration uncertainty into account. If we add the A–C flux contributions at 15 GHz and take the ratio with the D component, we get $7.9 \pm 0.3$ (Winn et al. 2003). The corresponding flux ratio at 140 GHz is $7.7 \pm 0.4$. The flux ratio at 91 GHz is slightly lower $6.6 \pm 0.5$, but here the A–C and D components are not entirely resolved, making the flux ratio measurement less certain (see Figure 1). Overall, the flux ratios seen at radio frequencies are consistent with our results at millimeter wavelengths and we detect no significant effect of differential magnification.

4.2. Molecular Absorption

We used an aperture with the same size as the restoring beam to extract spectra toward the continuum images A–C and D in PMN 0134–0931. The data cubes used for extracting the spectra were cleaned using Briggs weighting with the robustness set to 0.5. This results in slightly lower angular resolution than that obtained using uniform weighting, but is necessary to maximize

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5 We use the same designation of the lens components as in Winn et al. (2003).
the sensitivity while still retaining sufficient angular resolution to separate the continuum components. A uniform weighting produced noisy spectral data and we were not able to definitively assess the absorption properties toward the E component separate from the A–C image.

We detect absorption of CO \( J = 2–1 \) and HCO\(^+\) \( J = 2–1 \) toward both the A–C and D components. The spectra are shown in Figure 3. The absorption profiles cover a total velocity range of \( \sim 400 \) km s\(^{-1} \) and consist of several distinct components. The depth of the absorption profiles is \( \lesssim 10\% \) of the continuum toward components A–C while it is \( \sim 40\% \) and 30\% toward the weaker D component for CO and HCO\(^+\), respectively. Overall, the absorption profiles of CO and HCO\(^+\) are similar, suggesting that they originate in the same molecular gas. Both the CO and HCO\(^+\) absorption profiles consist of a “narrow” component (seen to the right in Figure 3), and a “wider” component. We fit Gaussian profiles to the absorption lines. The best result is obtained with three Gaussian components for the D component, two for the “wide” and one for the “narrow” profile. The A–C component only requires two Gaussian components to give a good fit. The results from the Gaussian fits are given in Table 3. The combined width of the “narrow” and “wide” CO and HCO\(^+\) absorption profiles is \( \sim 200 \) km s\(^{-1} \) toward both the A–C and D images. The CO profile toward the D component is even wider, approaching \( \sim 250 \) km s\(^{-1} \). The overall shapes of the profiles are similar toward the A–C and D continuum components, despite probing molecular gas separated by 5 kpc in the lens plane.

While the overall shapes of the absorption profiles are comparable toward the A–C and the D continuum components, they do shift in velocity by a significant amount. The difference in intensity weighted velocity across the entire absorption profile for the CO and HCO\(^+\) lines along the two sightlines toward the A–C and D lens images is \( 212 \pm 6 \) km s\(^{-1} \).
two Gaussian profiles to each absorption profile gives a velocity difference of $215 \pm 8\,\text{km}\,\text{s}^{-1}$. Combining a Gaussian fit to the “narrow” absorption components and an intensity weighted velocity for the “broad” absorption profiles gives a slightly larger velocity difference of $218 \pm 8\,\text{km}\,\text{s}^{-1}$. All of these estimates are consistent with each other within the errors, and we adopt $\Delta v = 215 \pm 8\,\text{km}\,\text{s}^{-1}$ as the velocity difference between the molecular absorption along the A–C and D lines of sight to PMN 0134−0931.

The observed opacity can be directly derived from the normalized flux $F(\nu)$ shown in Figure 3 as $\tau_{\text{abs}}^{\nu} = -\ln(1 - F(\nu))$. If $F(\nu) = 0$ the absorption is saturated and only a lower limit to the column density can be derived. The absorption profiles toward PMN 0134−0931 do not appear to be saturated although the true opacity $\tau_{\nu}$ of the absorbing gas may be higher than $\tau_{\text{abs}}^{\nu}$ if the filling factor of absorbing gas, $f_{\nu}$, is less than unity:

$$\tau_{\nu} = -\ln\left[1 - \frac{1}{f_{\nu}}(1 - e^{-\tau_{\text{abs}}^{\nu}})\right].$$

Assuming that $f_{\nu} = 1$ and consequently, $\tau_{\nu} = \tau_{\text{abs}}^{\nu}$, a lower limit to the column density of both CO and HCO$^+$ can be derived from

$$N_{\text{tot}} = \frac{8\pi}{c^2} \frac{\nu^3}{g_f A_{J, J+1}} \int f(T_\nu) d\nu,$$

where $g_f$ is the statistical weight of level $J$, $A_{J, J+1}$ is the Einstein coefficient for transition $J \rightarrow J+1$, and the function $f(T_\nu)$ is

$$f(T_\nu) = \frac{Q(T_\nu) e^{E_J/kT_\nu}}{1 - e^{-h\nu/kT_\nu}}.$$

In local thermal equilibrium (LTE), the partition function $Q(T_\nu) = \sum_j g_j e^{-E_j/kT_\nu}$, where $E_j$ is the energy of level $J$ and $T_\nu$ is the excitation temperature of the molecule in question. The observed quantity needed for deriving the column density is the velocity integrated opacity $\tau_{\nu}$.

The results for CO and HCO$^+$ are given in Table 4 for the A–C and D components. It is clear that the opacities of both CO and HCO$^+$ are significantly higher toward the D component. This is consistent with the optical reddening reported by Hall et al. (2002). In particular, the CO opacity toward the D component is one of the highest values seen in molecular absorption line systems. This is largely due to the large width of the absorbing profile and not just its depth. The column densities listed in Table 4 are derived assuming excitation temperatures of 4.8 K and 10 K. A $T_\nu = 4.8\,\text{K}$ corresponds to the Cosmic Microwave background (CMB) temperature at $z = 0.7645$. With $T_\nu = 10\,\text{K}$ for both HCO$^+$ and CO, the ratio of $N_{\text{CO}}/N_{\text{HCO}^+}$ is $\sim500$ toward the A–C component and $\sim1400$ toward the D component. Typical column density ratios seen in other absorption line systems, derived using $T_\nu = 10\,\text{K}$, range from $\sim670$ (B1504+377; Wiklind & Combes 1995) to $\sim800$ (PKS1413+135; Wiklind & Combes 1997). In the other absorption systems the CO and/or the HCO$^+$ lines are saturated and no estimate of the abundance ratio can be obtained. The high CO-to-HCO$^+$ abundance ratio toward the D component suggests that either the molecular gas seen here is of a different nature than the typical diffuse gas observed in other high-redshift molecular absorbers or that the covering factor $f_{\nu}$ is $<1$ for the HCO$^+$ absorption. The CO and HCO$^+$ molecules have different critical densities and may therefore exhibit different excitation temperatures, with HCO$^+$ likely to have $T_\nu \approx T_{\text{CMB}}$ and CO to have $T_\nu \approx T_{\text{CMB}}$. Assuming $T_\nu = 4.8\,\text{K}$ for HCO$^+$ and $T_\nu = 10\,\text{K}$ for CO, would increase the $N_{\text{CO}}/N_{\text{HCO}^+}$ ratio by a factor 1.7. It is worth noting that the abundance ratio would also increase if we assumed $T_\nu = 4.8\,\text{K}$ for both HCO$^+$ and CO. In this case, by a factor $\sim1.3$.

Given the strength and signal-to-noise ratio of the HCO$^+$, $J = 2–1$ absorption, the HCN, $J = 2–1$ should be clearly detectable if the $N_{\text{HCO}^+}/N_{\text{HCN}}$ abundance ratio is similar to what is seen in other molecular absorption line systems with optically thin transitions (e.g., Wiklind & Combes 1996a, 1997). Absorption is indeed seen where we expect the redshifted HCN, $J = 2–1$ line for both the A–C and D components, but unfortunately, that frequency range is affected by interference, making a derivation of the integrated opacity and column density highly uncertain. We therefore refrain from making a statement of the HCN column density. The $\text{H}_2\text{O}\,J = 3_{13} – 2_{02}$ transition is located at the very edge of our B3 data. Although a potential line is seen at 5$\nu$ toward the D continuum component, the proximity to the band edge makes this line less reliable. The H$2$O line is not detected toward the A–C component.

4.3. Molecular Emission

Because at least one of the lensing galaxies is gas-rich we searched for CO $J = 2–1$ in emission. We extracted a spectrum from the data cube using a circular aperture with a diameter of
1.0 (7.48 kpc at the redshift of the lens) centered halfway between components A–C and D. We binned the spectrum to a velocity resolution of 13.4 km s$^{-1}$, resulting in a channel to channel rms noise of 95 $\mu$Jy/beam. No emission was detected and assuming a velocity width of 200 km s$^{-1}$ the 5$\sigma$ upper limit to the molecular mass is $3.5 \times 10^9 M_\odot$. The molecular mass
where $\Delta v$ is expressed in Jy km s$^{-1}$, the luminosity distance $D_L$ in Mpc, and $\nu_{\text{obs}}$ in GHz. We used $\alpha = 4.6 \times 10^7 M_\odot$ (km s$^{-1}$ pc$^2$)$^{-1}$ for the conversion between CO luminosity and H$_2$ mass.

$$M_{H_2} = \alpha L'_{\text{CO}} = 3.25 \times 10^7 \alpha \times [S_{\text{CO}} \Delta v] \nu_{\text{obs}}^{-2} D_L^2 (1 + z)^{-3} M_\odot,$$

(4)

where $[S_{\text{CO}} \Delta v]$ is the opacity measured from the normalized flux.

5. Discussion

5.1. Kinematics

Both the CO $J = 2–1$ and HCO$^+$ $J = 2–1$ absorption lines toward the A–C lens components extend for $\sim 200$ km s$^{-1}$, divided into two main absorption components. A similar total width is seen for HCO$^+$ toward the D lens component. The CO $J = 2–1$ absorption toward the D component is even wider, extending over $\sim 250$ km s$^{-1}$. While the absorption seen toward the A–C component may be composed of contributions toward all three continuum images of the background QSO, separated by up to 1.3 kpc in the lens plane, the D component represents a very narrow line of sight through the lens, probably $\lesssim 1$ pc. In other molecular absorption lines the line widths range from a few km s$^{-1}$ to tens of km s$^{-1}$ (e.g., Wiklind & Combes 1997, 1998). Only PKS 1830–211 has molecular absorption lines approaching $\sim 100$ km s$^{-1}$ in width (Wiklind & Combes 1996b, 1998; Muller et al. 2014). This system is also gravitationally lensed and provides two lines of sight through the disk of a spiral galaxy. Molecular absorption is seen along both sightlines, with a velocity separation $\sim 148$ km s$^{-1}$, providing a measure of the rotational motion of the lensing galaxy. The absorption profiles seen along the two lines of sight in PKS 1830–211 are very different in shape and width and the 100 km s$^{-1}$ line widths are caused by highly saturated absorption lines. The molecular absorption seen toward the QSO B1504+377 at $z = 0.67$ also consists of two distinct absorption lines, separated by $\sim 330$ km s$^{-1}$ (Wiklind & Combes 1996a). In this system the absorption occurs in the host galaxy of the QSO and the two absorption lines occur along a single line of sight. The H I 21 cm absorption profile extends across the two molecular absorption complexes and shows that this is one continuous absorption system with a total velocity extent approaching 600 km s$^{-1}$ (Kanekar & Chengalur 2008). In this case, both the molecular and atomic absorption is likely to be associated with a fast neutral gas outflow, similar to those seen in lower redshift AGNs (Morganti et al. 2005).

Large line widths, such as the molecular absorption profiles seen toward PMN 0134–0931, can arise if the line of sight passes through an inclined gas-rich disk. The velocity envelope of the absorbing gas obtained by integrating along a line of sight through an axisymmetric disk depends on the inclination of the galaxy, the shape of the rotation curve, the radial extent of the absorbing gas and its velocity dispersion (Kregel & van der Kruit 2004, 2005). A velocity dispersion of $\sim 30$ km s$^{-1}$, a flat rotation curve and an inclination $i \gtrsim 60^\circ$ produce a velocity profile of width $\sim 200$ km s$^{-1}$. These parameters can be relaxed by making the radial extent of the gas distribution larger. Of course, molecular gas is not smoothly distributed but exists in discrete clouds and clumps. The velocity profile obtained by integrating along a line of sight represents an envelope and the fact that it is largely “filled” with absorbing molecular gas indicates that there are several absorbing clouds along the lines of sight to PMN 0134–0931. Another possibility is that the absorbing profiles are caused by lines of sight penetrating the disk of two galaxies, which happens to have similar relative velocities. The lens models, however, do not favor such a scenario. The presence of two galaxies, with a projected distance of only $\sim 3$ kpc in the lens plane (Keeton & Winn 2003) means that there is a possibility that the lensing galaxies are engaged in a merger process, with disturbed kinematics and non-circular motions, possibly with tidal arms crossing the line of sight to the background QSO.

The velocity difference between the absorption toward the A–C and D lens components is $215 \pm 8$ km s$^{-1}$ (see Section 4). This difference is also seen in the H I 21 cm and OH 18 cm absorption (Kanekar & Briggs 2003; Kanekar et al. 2005; Figure 4), although in these cases the background continuum sources were not resolved. The two-galaxy configuration implied by the lens model (Keeton & Winn 2003) has one of the galaxies centered just south of lens component C. If this galaxy extends across the A–C and D components, the molecular absorption may probe the rotation of a disk. In this case the absorption can be used to estimate the dynamical mass of one of the lensing galaxies. This, however, requires knowledge of the exact location and orientation of the lensing galaxy. Currently, neither observational data nor the lens models provide such information. A minimum mass can be derived by assuming that the center of the lens is mid-way between the A–C and D components and that the velocity separation probes the rotational velocity of the disk: $M_{\text{min}} \approx 7 \times 10^7 / \sin i M_\odot$. However, as discussed above, due to the small projected distance between the two lensing galaxies, they may be gravitationally interacting, hence the kinematics of this system may not represent ordered motion.

### Table 4

| Transition | Component | $\Delta v$ (km s$^{-1}$) | $\sigma_v$ (km s$^{-1}$) | $\int \tau_{1/2} \, dv$ (km s$^{-1}$) | $N$ (cm$^{-2}$) |
|------------|-----------|-------------------------|-------------------------|---------------------------|---------------|
| CO($J = 2–1$) | A-C       | 4.48                    | 0.017                   | 5.25 ± 1.20               | 1.30 ± 0.41 $\times 10^{16}$ |
|            | D         | 4.48                    | 0.013                   | 70.26 ± 6.96              | 1.73 ± 0.24 $\times 10^{17}$ |
| HCO$^+$($J = 2–1$) | A-C     | 5.79                    | 0.036                   | 7.20 ± 0.65               | 2.03 ± 0.32 $\times 10^{13}$ |
|            | D         | 5.79                    | 0.070                   | 35.14 ± 3.21              | 9.89 ± 0.16 $\times 10^{13}$ |
|            |           |                         |                         |                           |               |

Note. $\sigma_v$ refers to the 1σ noise in the opacity measured from the normalized flux.

This table provides the opacity and column densities for the observed transitions.

- CO($J = 2–1$) for components A-C and D
- HCO$^+$($J = 2–1$) for components A-C and D

The entries include $\Delta v$, the velocity separation, $\sigma_v$, the velocity noise, $\int \tau_{1/2} \, dv$, the integrated H I column density, and $N$, the CO column density at 864.73$^\circ$.

The values are consistent with the expected kinematics of the lensing system, providing insights into the dynamical properties of the galaxies involved.
5.2. *Column Density*

The high CO column density seen toward the D lens component is unusual among the molecular absorption systems observed to date, both in distant galaxies as well as in our own Galaxy (Lucas & Liszt 1996). The column density ratio $N_{\text{CO}}/N_{\text{HCO}^+}$ is at least ~2 times higher than earlier estimates along Galactic and high-z sightlines, and almost three times higher than what is seen toward the A–C component in PMN 0134−0931. This high abundance ratio does not seem to be due to an anomalously low $N_{\text{HCO}^+}$. The column density of HCO$^+$ along the D component is $1.7 \times 10^{14}$ cm$^{-2}$ (Table 4), significantly higher than what is typically seen in absorption of diffuse molecular gas. Lucas & Liszt (1996) found an average $N_{\text{HCO}^+}$ column density of $2.6 \pm 3.4 \times 10^{13}$ cm$^{-2}$ in a sample of 17 lines of sight through diffuse molecular gas in the Milky Way galaxy, almost a factor of 10 lower than the column density we derive for HCO$^+$ toward the D component. Our estimate is, however, similar to the average HCO$^+$ column density of $2 \times 10^{14}$ cm$^{-2}$ seen in Infrared Dark Clouds (Sanhueza et al. 2012). The CO column density is also significantly higher than any previously value derived from unsaturated absorption lines. This suggests that the absorption toward the D component occurs in a dense molecular cloud core rather than the typical diffuse molecular gas.

This interpretation is corroborated by the H I 21 cm absorption profile (Kanekar & Briggs 2003). In Figure 4, we compare the H I 21 cm absorption profile of Kanekar et al. (2012) with that of the HCO$^+$ $J = 2\rightarrow1$ absorption profile presented in this paper. The H I profile has the same broad character as seen in the molecular absorption, with similar overall velocity spread. The H I 21 cm observations did not resolve the lensing components but comparing the H I profile with the molecular profiles it is possible to distinguish which part of the H I 21 cm absorption is associated with the A–C and the D components, respectively (Figure 4). There are two interesting differences between the mm-wave molecular and atomic absorption profiles; toward the A–C lens component, the CO and HCO$^+$ absorption consists of two distinct line components while the H I 21 cm absorption consists of a single smooth profile. Still, the overall widths are the same. This suggests that the absorbing gas consists of two denser molecular clumps embedded in a smooth atomic component. Towards the D lens component, on the other hand, the CO and HCO$^+$ absorption profiles consist of three distinct profiles, two of which are much less pronounced in the H I 21 cm absorption and in the case of the “narrow” molecular absorption, essentially without any H I absorption altogether. This suggests that this absorption arises in a gas component that is completely molecular. This is consistent with this being a dense molecular cloud, as inferred from the high $N_{\text{CO}}/N_{\text{HCO}^+}$ column density ratio. The OH 1665 MHz absorption toward PMN 0134−0931 closely follows that of H I (Kanekar et al. 2005), with a pronounced absence of OH in two of the HCO$^+$ and CO absorption components toward the D image. As line widths of CO and HCO$^+$ in dark molecular clouds are typically only a few km s$^{-1}$ (Lucas & Liszt 1996; Sanhueza et al. 2012), the overall large line widths seen in PMN 0134−0931 as well as the large $N_{\text{CO}}$ and $N_{\text{HCO}^+}$ values are simply due to a large number of absorbing molecular clouds lined up along the line of sight.

Kanekar et al. (2012) provide a 4-component Gaussian fit to their OH 1667 MHz spectrum, with two components at positive velocities (relative to $z = 0.7645$) and two at negative velocities. We use this to infer the OH column density toward lens components A–C and D, assuming that, like the mm-wave absorption, the positive velocity OH absorption arises against A–C and the negative velocity absorption against D. The OH column density estimate also requires the covering factors of the A–C and D components. For this, we use the flux densities of the different components measured by Winn et al. (2003) and the low-frequency spectral index of $\alpha = −0.69$ (Winn et al. 2003) to estimate the fraction of the total flux density at ~945 MHz (the redshifted OH 1667 MHz line frequency) in components A–C and component D. We obtain flux density fractions of $\approx0.85$ in components A–C and $\approx0.15$ in component D, assuming that the other components do not contribute significantly to the 945 MHz flux density. For a typical OH line excitation temperature of 10 K,
this then yields OH column densities of $N_{\text{OH}} = 2.1 \times 10^{15}$ cm$^{-2}$ and $2.1 \times 10^{16}$ cm$^{-2}$ against components A–C and D, respectively, assuming that the covering fractions of components A–C and D are the same as their fractional contribution to the total flux density. Comparing these to the HCO$^+$ column densities along the two sightlines yields HCO$^+$ to OH column density ratios of $\approx 0.017$ and $\approx 0.0082$ toward A–C and D, respectively. The former is similar to estimates of this ratio ($\approx 0.03$) in diffuse gas in both the Milky Way and high-$z$ galaxies (e.g., Lucas & Liszt 1996; Kanekar & Chengalur 2002), but the latter is significantly lower. This reinforces our suspicion that the sightline toward component D is very different from typical sightlines through spiral galaxies.

5.3. Summary

The gravitational lens system PMN 0134–0931 consists of two galaxies at $z = 0.7645$ with a small projected separation on the sky. The lensing configuration gives rise to six lensed images. Absorption of ionized, atomic and molecular gas probe kinematically distinct lines of sight through this system. The molecular absorption is seen toward two lines of sight, separated by $\approx 5$ kpc in the lens plane. The absorption lines shift by $215 \pm 8$ km s$^{-1}$ between the two lines of sight, possibly due to the rotational motion of one of the lensing galaxies. The width of the absorption profiles is $\approx 200$ km s$^{-1}$. This suggests that the absorption occurs in an inclined gas-rich disk with an approximately flat rotation curve and a cloud–cloud velocity dispersion of $\approx 30$ km s$^{-1}$.

The column densities of CO and HCO$^+$ toward the A–C component are similar to other extragalactic molecular absorption systems but it is unusually high toward the D component. This is likely due to the presence of molecular gas more dense than the diffuse molecular gas most commonly seen in absorption. The data on the ISM and its kinematics can potentially be used to further refine the lens model and help to understand the nature of this intriguing gravitational lens system. The interpretation is currently hampered by the lack of accurate information on the location and orientation of the lensing galaxies.

This paper makes use of the following ALMA data: ADS/JAO.ALMA#2015.1.00582.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. N.K. acknowledges support from the Department of Science and Technology via a Swarnajayanti Fellowship (DST/SJF/PSA-01/2012-13).

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