THE COMPLEX MOLECULAR ABSORPTION LINE SYSTEM AT $z = 0.886$ TOWARD PKS 1830–211

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ABSTRACT

New single-dish and millimeter wave interferometer observations of the molecular absorption line system in the gravitational lens to PKS 1830–211 at $z = 0.88582$ are presented. Self-calibrated interferometer data show unequivocally that the previously detected absorption component is associated with the gravitationally lensed southwest image of the background source. A second absorption line of HCO$^+$ (2$→$1) at $z = 0.88582$ is detected. This component is shifted in velocity by $-147$ km s$^{-1}$ relative to the main absorption line and is shown to be associated with the northeast image. A few additional absorption lines are presented. Upper limits to absorption and emission lines from the possible absorption system at $z = 0.1927$, seen in 21 cm H $\alpha$ by Lovell et al., are reported. Alternatively, there could be only one absorbing system at $z = 0.88582$, with the H $\alpha$ line attributed instead to the PS molecule.

Subject headings: ISM: molecules — BL Lacertae objects: individual (PKS 1830–211) — galaxies: abundances — galaxies: ISM — gravitational lensing — quasars: absorption lines

1. INTRODUCTION

The molecular interstellar medium (ISM) in galaxies at redshifts of up to $z \approx 0.9$ has been studied through the use of absorption of molecular rotational transitions (cf. Wiklind & Combes 1996a, 1996b; Combes & Wiklind 1995). Detection of several different lines of molecules such as CO, HCO$^+$, HCN, HNC, CS, N$_2$H$^+$, H$_2$CO, etc., allows the derivation of accurate excitation temperatures, column densities, and abundance ratios (Wiklind & Combes 1994, 1995, 1996a, 1996b). Four molecular absorption line systems are known to date; in two of them the absorption occurs in the host galaxy to the AGN, and two represent truly intervening galaxies. Since the distribution of molecular gas in galaxies is usually centrally concentrated, the likelihood of encountering a molecular cloud is higher if the line of sight passes close to the center of an intervening galaxy. This means that the likelihood for gravitational lensing is also high and, indeed, in each of the two systems where absorption occurs in an intervening galaxy, that galaxy acts as a gravitational lens to the background source (Wiklind & Combes 1995, 1996a).

The uses of molecular absorption lines are manifold. Apart from studying the physical and chemical properties of molecular gas in distant galaxies, they can be used as probes of very small scale structures in the molecular gas. They can also be used as cosmographic probes, to set upper limits to the temperature of the cosmic microwave background radiation and to constrain the geometry in gravitationally lensed systems. The molecular ISM is probed on a scale of a few tenths of a parsec, limited only by the angular extent of the background source. The main uncertainty in the molecular gas properties derived from the absorption lines arises from our ignorance of possible small-scale structures in the ISM, on scales smaller than the angular extent of the background source (e.g., Wiklind & Combes 1997).

In this article, we concentrate on the absorption-line system originating in a galaxy that acts as a gravitational lens at $z = 0.886$ (Wiklind & Combes 1996a). The galaxy absorbs the continuum of the strong flat-spectrum radio source PKS 1830–211. This radio source has long been considered a gravitational lens candidate on the basis of the radio structure (Rao & Subrahmanyan 1988; Jauncey et al. 1991). Since optical and near-infrared searches for an optical counterpart to the radio source and the lensing galaxy have remained unsuccessful (cf. Djorgovski et al. 1992), the modeling of the lensing system has lacked redshift information (Kochanek & Narayan 1992; Nair, Narasimha, & Rao 1993). The galaxy at $z = 0.886$ was discovered by searching for molecular absorption lines in the 3 and 2 mm bands (Wiklind & Combes 1996a). A second intervening system has been reported at $z = 0.193$, seen through 21 cm H $\alpha$ absorption by Lovell et al. (1996).

We present new molecular absorption data for the galaxy at $z = 0.886$ as well as upper limits to molecular absorption and emission for the $z = 0.193$ system. We also discuss what can be inferred regarding the mass of the lensing galaxy and the redshift of the background source.

2. OBSERVATIONS AND DATA REDUCTION

Our data were obtained using the IRAM millimeter wave interferometer situated on Plateau de Bure in France, the single-dish IRAM 30 m telescope on Pico Veleta in Spain, and the 15 m SEST (Swedish ESO Submillimeter Telescope) on La Silla in Chile. The interferometer observations were done on several occasions during 1995 and 1996. The single-dish observations were likewise obtained during several observing runs in 1995 and 1996.

At the IRAM 30 m telescope, we used 3, 2, and 1.3 mm SIS receivers tuned to the redshifted frequency of the observed transition. The observations were made using a nutating subreflector with a frequency of 0.5 Hz and with a throw of $\pm 90^\circ$ in azimuth. Typical system temperatures in the $T_A^*$ scale were 400–600 K. The weather conditions were good during most observing sessions. Pointing, focusing, and calibration were done before each observation. As back ends, we used narrowband autocorrelators, giving a veloc-
ity resolution of approximately 0.7 km s$^{-1}$ and a bandwidth of 400 km s$^{-1}$. At the SEST, we used 3 and 2 mm SIS receivers, with typical system temperatures of 200–300 K. Here we used an AOS with a bandwidth of 1200 km s$^{-1}$ and a velocity resolution of 0.7 km s$^{-1}$. These observations were done in a dual beam-switch mode, where the beam is displaced 12’ in azimuth at a frequency of 6 Hz. The SEST data were obtained under good weather conditions. Pointing and calibration where done as at IRAM.

The interferometer data were obtained with the standard BC configuration (see Guilloteau et al. 1992). The array comprised four 15 m telescopes. The receivers were 3 mm SIS, giving a typical system temperature of 400–500 K. PKS 1830–211 itself was used as a phase reference, while bandpass and amplitude calibrations were also done using NRAO 530, 3C 454.3, and W3O H. The data reduction was made with the standard CLIC software. Due to the low elevation of PKS 1830–211, we obtained a beam of 6′ × 2′4. This appears insufficient to resolve two images separated by only 1′, but because of the high signal-to-noise ratio, we were able to fit the integrated line profile and the phase center, as a function of frequency, directly from the visibilities. We also made a two point sources fit, which gave the relative positions of the two images and their relative fluxes.

The accuracy of the measurement depends on the inherent uncertainty in the chopper-wheel calibration method, as well as the pointing of the telescope. The overall accuracy for a single observation of the intensities is around 5%–10% for the interferometer data and 10%–20% for the single-dish data.

3. RESULTS

3.1. The Location of the $z = 0.886$ Absorption

In our first study of the molecular absorption line system toward PKS 1830–211, we found that the HCO$^+$ (2 → 1), HCN (2 → 1), and possibly the HNC (2 → 1) lines were heavily saturated (Wiklind & Combes 1996a). Yet, the depths of these absorption lines were only 36% of the total continuum. Since the magnification ratio derived from long-wavelength interferometer data is 1.8 (Nair et al. 1993), corresponding to a flux fraction of ~36% for the southwest and 64% for the northeast core, respectively, we concluded that the molecular gas only covers the southwest core, with a high covering factor (close to 100%). The present interferometric results confirm that only the southwest component is absorbed around $V = 0$.

In Figure 1 we show the HCO$^+$ (2 → 1) spectrum obtained with the Plateau de Bure interferometer. The low declination of PKS 1830–211 makes imaging difficult, in part because of a north-south elongated beam and the large air mass. The continuum is, however, strong enough to allow a self-calibration of the data. We made a Gaussian fit of the source directly from the visibility data, and traced the location of the phase center as a function of frequency. The accuracy is very good in R.A. (~0.05) and slightly worse in decl. (~0′1). The two top panels in Figure 1 show the relative phase in R.A. and decl. as a function of velocity across the absorption profile. From the data obtained in 1995 September and October, the maximum shifts are $\Delta \varpi = 0′.22$ and $\Delta \delta = 0′.28$. From the 1996 April data, we get $\Delta \varpi = 0′.24$ and $\Delta \delta = 0′.26$ (see also Fig. 3).

If the flux fractions from the northeast and southwest cores are $f_1$ and $f_2$, respectively ($f_1 + f_2 = 1$), the shift of the phase center along the line joining the cores is

$$\Delta \varpi = \beta(v)f_2r \sin \psi$$

(1)

$$\Delta \delta = \beta(v)f_2r \cos \psi$$

(2)

where $\beta(v)$ is the fraction of continuum flux from the southwest core that is covered by optically thick molecular gas of velocity $v$, $r$ is the separation of the two components, and $\psi$ is the position angle of the line joining the two cores, measured from north to east. From the 15 GHz VLA continuum map presented by Subrahmanyan et al. (1990), we derive $r = 0′.98$ and $\psi = 44^\circ$. Expressing the flux fractions in terms of the magnification ratio $R = f_1/f_2$, we get $\beta = (1 + R)\Delta \varpi/(r \sin \psi)$. Using the magnification ratio $R$ derived from long-wavelength interferometry of 1.8 (Nair et al. 1993) and assuming that the covering factor $\beta$ is 100% for the southwest component, the phase center should shift $\Delta \varpi \approx 0′.24$ and $\Delta \delta \approx 0′.25$, which is consistent with the shift that we see in Figure 1.

Frye, Welch, & Broadhurst (1997) observed PKS 1830–211 with the BIMA interferometer and derived a magnification ratio of 1.14 ± 0.05 by resolving the two continuum components. Since the HCO$^+$ (2 → 1) line is manifestly optically thick, as seen through the detection of the
Plateau de Bure observations, we have tried to retrieve the magnification ratio from a two-point-sources fit of the visibility data. The fits were very robust, completely independent of the initial parameters, and revealed an R.A. and decl. separation between the two images exactly consistent with $r = 0.98$ and $\psi = 44^\circ$ in all the 136 channels without absorption. In Table 1 we show the magnification ratios obtained at the various epochs. Although the absolute calibration is not so precise, we believe that the relative ratios between the two components is accurate. Although the magnification ratio has changed from 1.8 $\pm$ 0.1 to 1.2 $\pm$ 0.1 between 1995 October and 1996 April, in concordance with the value derived by Frye et al. (1997), the lower continuum level measured by us is in agreement with a covering factor of $\sim 1$ for the southwest component (see § 4.2).

3.2. A Second Absorbing Cloud at $z = 0.88489$

We have detected a second absorption component situated at a velocity of $-147$ km s$^{-1}$ relative to the main HCO$^+$ ($2 \leftarrow 1$) absorption at $z = 0.88582$. The second component is hereafter referred to as the “satellite.” The HCO$^+$ ($2 \leftarrow 1$) line has been observed extensively during a monitoring campaign at both the IRAM 30 m and SEST 15 m telescopes. Averages of data obtained during 1996 are shown in Figure 2, where the two dashed vertical lines mark zero velocity and $-147$ km s$^{-1}$ in a heliocentric velocity scale in the rest frame of the $z = 0.88582$ absorber. The satellite line is not seen in the HCO$^+$ ($3 \leftarrow 2$) spectrum. Frye et al. (1997) could have detected this component in 1996 March (since the line was present at this epoch; see Fig. 3), but their lower signal-to-noise ratio prevented the detection.

Could the second absorption line be associated with the $z = 0.193$ H$\alpha$ absorber rather than the one at $z = 0.886$? The only line at $z = 0.193$ that could be in the vicinity of the observed frequency of the satellite line at 94.635 GHz is the redshifted CO ($1 \leftarrow 0$) line at 96.650 GHz. The difference is in excess of 2 GHz, corresponding to a velocity difference of $\sim 6200$ km s$^{-1}$ in the rest frame of the $z = 0.193$ absorber. It is therefore highly unlikely that the satellite absorption is associated with this system. We conclude that the satellite line is a second HCO$^+$ ($2 \leftarrow 1$) line at a blueshifted velocity of $-147$ km s$^{-1}$ relative to the redshift $z = 0.88582$ (corresponding to a redshift of $z = 0.884896 \pm 0.00001$).

While the main absorption line at $V = 0$ has a depth of 38%–40% of the total continuum, the satellite line has a depth of only 7%. Measured in antenna temperature, this corresponds to 1.5 mK and 6 mK in the SEST and IRAM data, respectively, as of 1996 April. The actual opacity, however, depends on the surface covering factor of the absorption. The separation of the northeast and southwest continuum components is $0.98$, corresponding to a distance of 5.6 kpc measured in the plane of the sky ($H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$). The satellite absorption can therefore be associated with only one of the continuum sources. Since the

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| Date     | Total Flux | NE/SW Ratio | $\beta_{max}$ |
|----------|------------|-------------|--------------|
| 1995 Oct | 1.5        | 1.8 $\pm$ 0.1 | 1.0          |
| 1996 Apr | 1.45       | 1.2 $\pm$ 0.1 | 0.9          |
| 1996 Sep | 0.93       | 1.0 $\pm$ 0.1 | 1.0          |

* Maximum covering factor of the southwest component.
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The flux contributions from the northeast and southwest components are ~60% and ~40%, respectively, the satellite absorption line either is optically thin or has a very small covering factor.

The satellite absorption line is clearly seen in the interferometer data (Fig. 3). The relative location of the phase center for $\Delta z$ is shown in the top panel. In addition to the positive shift of the phase center already established for the main absorption around $V = 0$ km s$^{-1}$, a shift is also seen at the velocity of the satellite line, but this time toward negative values. This shows that the phase center moves partly toward the southwest continuum component at the velocity of the satellite absorption. The second absorption component must therefore originate in front of the northeast continuum core. We are thus seeing molecular gas from two different parts of the intervening galaxy.

Two absorption components, separated by 330 km s$^{-1}$, are also seen at $z = 0.673$ toward the radio source B3 1504+377 (Wiklind & Combes 1996b). In this case, the absorption occurs in the galaxy hosting the radio source. The galaxy is close to edge-on and the separation of the two absorption lines is caused by noncircular velocities along a single line of sight within the disk of the host galaxy, most likely caused by the presence of a barred potential. The line of sight to the two images of the continuum core of PKS 1830−211 passes through the intervening galaxy at ~1.8 and ~3.8 kpc (southwest and northeast components, respectively) from the lens center (Nair et al. 1993). A normal rotation curve (and circular orbits) are sufficient here to account for the observations.

We derived column densities using the formalism presented in Wiklind & Combes (1995, 1997). The HCO$^+$ column density of the satellite absorber, derived using 60% of the total flux, is only $7 \times 10^{12}$ cm$^{-2}$ (however, we can not exclude the case of a highly saturated line with a small covering factor). Using 40% of the total flux for the main line, we find an HCO$^+$ column density $>5 \times 10^{11}$ cm$^{-2}$. This value is derived from the averaged monitoring data for 1996 and is slightly higher than the column density reported in Wiklind & Combes (1996a). Since the main line is heavily saturated, the difference is due to the much better signal-to-noise ratio of the new data. The column densities have been derived using an excitation temperature $T_{ex} = 6$ K. Integrating the $J = 3 \leftrightarrow 2$ spectrum over the extent of the $J = 2 \leftrightarrow 1$ line sets a $3 \sigma$ upper limit to the excitation temperature of 8 K (a $2 \sigma$ limit implies $T_{ex} < 6$ K).

### 3.3. The $z = 0.193$ 21 cm H I Absorber

We searched for redshifted CO (1 $\leftrightarrow$ 0) absorption and/or emission as well as HCO$^+$ (2 $\leftrightarrow$ 1) absorption at $z = 0.19267$. Neither emission nor absorption was found. The CO and HCO$^+$ spectra are shown in Figure 4.

#### 3.3.1. Limits to the CO and HCO$^+$ Column Densities

The continuum level at the redshifted frequency of the CO (1 $\leftrightarrow$ 0) and HCO$^+$ (2 $\leftrightarrow$ 1) lines are 50 mK and 26 mK at the SEST telescope. However, when deriving upper limits to the column density for molecular absorption, we must take the separate flux contributions into account. While the 21 cm H I absorption only occurs over the northeast component (Lovell et al. 1996), putative molecular absorption can occur in front of both components. In Table 2 we give

![Figure 3](image-url)  
Fig. 3.—Results of the fit of visibility data from 1996 April observations. The integrated spectrum is shown at the bottom and the phase center position in right ascension is shown at the top. It is clear that the $V = -147.5$ km s$^{-1}$ component is absorbed in front of the northeast image.

| TABLE 2
Non-detection of Absorption at $z = 0.19267$ |
| Molecule | Transition | $v_{\text{rest}}$ | $v_{\text{obs}}$ | $T_{\text{ex}}$ | $N_{\text{tot}}$ | $N_{\text{H I}}$ |
|-----------|------------|-----------------|-----------------|--------------|----------------|---------------|
|           |            | (GHz)           | (GHz)           | (mK)         | (cm$^{-2}$)    | (cm$^{-2}$)    |
| CO        | 1 $\leftrightarrow$ 0 | 115.271204      | 96.650          | 50           | $<3 \times 10^{15}$ |                |
| HCO$^+$   | 2 $\leftrightarrow$ 1 | 178.375065      | 149.559         | 26           | $<3 \times 10^{12}$ | $<2 \times 10^{-5}$ |

$a$ Rest frequency of the observed molecules, from Lovas 1992.

$b$ Derived from $v_{\text{obs}} = v_{\text{rest}}(1 + z)$.

c Continuum level measured in $T_{A_{\text{ex}}}$.

d Ratio of molecular column density and H I (see text for details).
upper limits for three cases: (1) the total continuum flux, (2) 60% of the flux, corresponding to the northeast component, and (3) 40%, corresponding to the southwest component. In all cases we assume an excitation temperature of 6 K. The ratio of the upper limits of the molecular column density to that of the H I is done for the northeast component, since this line of sight causes the atomic absorption at $z = 0.193$.

We derived the H I column density from the spectra presented in Lovell et al. (1996) by fitting two Gaussian profiles. The resulting column density is $N_{HI} = 1.5 \times 10^{18} \text{ cm}^{-2}$, where $T_s$ is the spin temperature and $f$ is the area filling factor. Since the H I absorption is only seen toward the northeast component $f = 0.6f'$, where the factor 0.6 corresponds to the flux contribution of the northeast component and $f'$ is the area covering factor of atomic gas for this component. Assuming a spin temperature of 100 K, which is typical for atomic hydrogen gas in the Milky Way, the column density of atomic gas is $2.5 \times 10^{20} f' \text{ cm}^{-2}$. For the abundance ratios given in Table 1, we set $f' = 1$.

Using a typical value for $N(H_2)/N(CO)$ of $10^4$, the abundance ratio of molecular and atomic hydrogen is $<0.25$ in the $z = 0.193$ absorber. This limit is not very illuminating, since the column density of atomic gas is relatively low, corresponding to an extinction of $A_V \approx 0.16$ mag (e.g., Savage et al. 1977). Since CO becomes self-shielded only at $A_V \gtrsim 1$ mag (e.g., Lucas & Liszt 1994), we do not expect a significant amount of CO at these low H I column densities. Molecular hydrogen, however, can still be present, since it becomes self-shielded at lower $N_{HI}$.

3.3.2. Limits to $M_{HI}$ from CO Emission

Our CO (1–0) spectra of the $z = 0.193$ H I absorption can also be used to derive an upper limit to the global molecular mass content of any intervening galaxy at this distance. The single-dish telescope beam has a FWHP size of 52" at a frequency of 96.65 GHz, corresponding to $\sim 143$ kpc at $z = 0.193$. Since atomic gas disks are considerably smaller than this, an intervening galaxy causing the 21 cm H I absorption at $z = 0.193$ must be within our telescope beam. The effective beam of the interferometer data is $6'' \times 2'4$ (16.5 $\times$ 6.6 kpc), with a noise rms of 10 mJy beam$^{-1}$. The field of view is the same as for the single-dish observation, since 15 m telescopes were used in both cases.

The single-dish CO spectrum shown in Figure 4 has a channel-to-channel noise rms of 1.0 mK when binned to a resolution of 17 km s$^{-1}$. No emission is evident in the spectrum, and we derive a 3 $\sigma$ upper limit to the integrated CO intensity by assuming a line width of 200 km s$^{-1}$ to be $<0.17$ K km s$^{-1}$. The CO (1–0) spectrum does have a high-frequency baseline curvature, which has been removed in the spectrum shown in Figure 4. The uncertainty in the derived integrated intensity is limited by this curvature, but only for emission more extended than 1000 km s$^{-1}$. Since wide emission profiles are rarely encountered, we believe that the baseline curvature is of little concern in this case. The interferometer data does not suffer from any baseline curvature, and gives a 3 $\sigma$ upper limit to the integrated CO intensity of $<0.09$ K km s$^{-1}$.

The CO line luminosity, expressed in K km s$^{-1}$ pc$^2$, can be written as

$$L'_{CO} = \Omega_{s+b} D_L^2 \frac{I_{CO}}{(1+z)^2} \text{ K km s}^{-1} \text{ pc}^2,$$

where $D_L$ is the luminosity distance, $I_{CO}$ is the velocity-integrated CO intensity expressed in K km s$^{-1}$, and $\Omega_{s+b}$ is the solid angle of the source brightness distribution convolved with the telescope beam, $\Omega_b$. For distant sources and single-dish telescopes, this convolution is dominated by the solid angle of the beam, and we can approximate it with $\Omega_{s+b} \approx \Omega_b \approx 26.56 \times B^2$, (e.g., Solomon et al. 1997), where $B$ is the FWHP of the telescope beam measured in arcseconds.¹ The mass of molecular gas is obtained by assuming a conversion factor between CO luminosity and...
the column density of $H_2$ of $M_{H_2} = \alpha L_{CO}$. We use a standard Milky Way conversion factor $\alpha = 4.6 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ (e.g., Solomon et al. 1997). With these values, our upper limits to $I_{CO}$ transform into a 3 $\sigma$ upper limit to the $H_2$ mass of $5 \times 10^9 M_\odot$ and $2.5 \times 10^9 M_\odot$ for the single-dish and interferometer data, respectively.

3.4. Additional Absorption Lines

In addition to the 12 absorption lines presented in Wiklind & Combes (1996a), we have detected additional absorption lines from CO (4 $\rightarrow$ 3), $H_2$CO (2$_{11}$ $\rightarrow$ 1$_{01}$), and $H^{13}$CN (2 $\rightarrow$ 1). The spectra are presented in Figure 5, together with a new spectrum of $H^{13}$CO$^+$ (2 $\rightarrow$ 1) obtained with the IRAM 30 m telescope.

For the first time, we detect one of the CO lines in this system. The redshift of the absorber is such that the three first rotational transitions of CO fall at frequencies unfavorable for ground-based observations. The CO (4 $\rightarrow$ 3) line, however, is shifted into the 1 mm band. We observed this line with the IRAM 30 m telescope in 1996 May, and the spectrum is presented in Figure 5a. The line is rather strong, with a depth almost equal to that of the saturated transitions of HCO$^+$ and HCN. Using 40% of the total flux and an excitation temperature of 6 K, the CO column density is $2 \times 10^{18}$ cm$^{-2}$. Should $T_e$ be higher, say 20 K, the column density becomes $0.2 \times 10^{18}$ cm$^{-2}$. For higher excitation temperatures, the column density increases again. The main uncertainty in this derivation is the continuum flux. Because of unstable weather conditions, it was not possible to derive $T_e$. We have used the continuum flux determined from the 3 and 2 mm bands, which corresponds to 1.2 Jy, and converted this to antenna temperature in the 1 mm band. Although indirect, the energy distribution of the radio source PKS 1830–211 is flat enough to make this approach viable. The excitation temperature of CO can be higher than the low values found for HCO$^+$, HCN, $N_2H^+$, CS, etc. (see Wiklind & Combes 1996a). This is owing to the lower electric dipole moment of CO, which makes it more easily collisionally excited and gives CO a higher level population at rotational levels $J \geq 3$ than found for HCO$^+$ and HCN. Different excitation temperatures for CO and the other molecular species are consistent with the weak-LTE conditions used to derive the excitation temperature, where it is assumed that the level population of each molecule is characterized by a unique temperature (that is: $T_e = T_{rot}$), but this temperature can be different from one molecular species to another (see Wiklind & Combes 1995, 1997).

We also report the detection of ortho-$H_2$CO through the $J_{K_aK_b} = 2_{11} \rightarrow 1_{01}$ line (Fig. 5b). This line appears to be non-saturated, with a maximum optical depth of $\sim 1$. The column density of ortho-$H_2$CO is $2 \times 10^{15}$ cm$^{-2}$, assuming $T_e = 6$ K and a flux fraction of 40%.

Absorption of $H^{13}$CO$^+$ has been reported in Wiklind & Combes (1996a), but the present spectra represent a significant improvement of the signal-to-noise ratio. The detection of this isotopic species was one of the main arguments in favor of a high $H^{13}$CO$^+$ (2 $\rightarrow$ 1) line opacity. The column density of $H^{13}$CO$^+$, derived assuming the same excitation temperature as for the main isotope of 6 K, is $2 \times 10^{13}$...

Fig. 5.—(a) CO (4 $\rightarrow$ 3), (b) $H_2$CO (2$_{11}$ $\rightarrow$ 1$_{01}$), (c) $H^{13}$CO$^+$ (2 $\rightarrow$ 1), and (d) $H^{13}$CN (2 $\rightarrow$ 1) absorption at $z = 0.88582$. All spectra except $H_2$CO have been obtained with the IRAM 30 m telescope. $H_2$CO was observed with the 15 m SEST. The velocity resolution is 9.2 km s$^{-1}$ for the CO spectrum, 2.6 km s$^{-1}$ for the $H_2$CO spectrum, and 3.25 km s$^{-1}$ for the $H^{13}$CO$^+$ and $H^{13}$CN spectra. The total continuum level has been normalized to unity, and the velocity scale is heliocentric in the rest frame of the $z = 0.88582$ absorber.
cm$^{-2}$. The H$^{12}$CO$^+$/H$^{13}$CO$^+$ ratio is thus $>25$, and possibly much higher. From the similar absorption depths of HCO$^+$ ($2-1$) and HCN ($2-1$), we inferred that the HCN line was also heavily saturated (Wiklind & Combes 1996a). This is confirmed by the detection of the H$^{13}$CN ($2-1$) line with the IRAM 30 m telescope (Fig. 5d). The column density of H$^{13}$CN is $6 \times 10^{12}$ cm$^{-2}$ (again using 40% of the total flux and adopting an excitation temperature of 6 K). The H$^{12}$CN/H$^{13}$CN ratio is $>50$.

4. Discussion

4.1. The Lensing Galaxy at $z = 0.886$

The detection of a second absorption line component at redshift $z = 0.886$, shifted in velocity relative to the main line and associated with the northeast image of the background source, opens up a unique possibility for deriving the dynamical mass of the central few kpc of the lensing galaxy. This is valuable information when modeling the lens, specifically when using time-delay measurements to derive cosmographic parameters such as the Hubble constant. At present, this is hampered by the nondetection of the lensing galaxy at optical and infrared wavelengths (e.g., Djorgovski et al. 1992). This is likely to change with new and more powerful infrared detectors.

It is, however, possible to use very simple but powerful arguments, based on the assumption that the lensing galaxy is a normal disk galaxy, to get reasonable ranges for the mass of the lensing galaxy as well as the redshift of the background radio source from the present data.

The observed line-of-sight velocity in a disk galaxy of inclination $i$, having a rotational velocity $V(R)$, is

$$V_{\text{obs}} = V(R) \cos \theta \sin i,$$

where $R$ is the galactocentric radius in the plane of the galaxy and $\theta$ is the angle from the line of nodes, as measured in the plane of the galaxy. $R$ and $\theta$ are related to the radius $r$ and angle $\phi$ measured in the plane of the sky through

$$R = r \left( \cos \phi + \frac{\sin \phi \sqrt{i^2 + 1}}{i^2} \right)^{1/2}, \tan \phi = \tan \theta \cos i.$$

If we assume (as will be justified below) that $i$ is small (i.e., $i \lesssim 30^\circ$), the differences between radii and angles measured in the plane of the sky and those in the plane of the galaxy are small ($\cos i \approx 0.87$). This is a reasonable assumption, since, as we will show below, the dynamical mass required to cause the image separation seen in PKS 1830–211 implies that the rotational velocity of the lensing galaxy is more than twice as large as the observed velocity separation of the main and satellite absorption lines (e.g., sin $i < 0.5$ and $i < 30^\circ$). If we also make the assumption that the rotation curve is similar in shape to those found in nearby galaxies, we can assert that the rotational velocity is approximately constant at radii $\gtrsim 2$ kpc. This is seen from an inspection of the rotation curves derived for all different types of spiral galaxies by Rubin et al. (1980, 1982, 1985). Two different lens models have been produced for PKS 1830–211 (Kochanek & Narayan 1992; Nair et al. 1993). They both agree that the center of the lensing galaxy is close to the center of the ring seen in radio interferometer data and that the lens has a small eccentricity. The model of Nair et al. (1993) places the center of the lens somewhat closer to the southwest image than the model of Kochanek & Narayan (1992). In the former case, the southwest and northeast cores are seen at projected distances of 1.8 kpc and 3.8 kpc from the center, respectively. In the model of Kochanek & Narayan, both cores are $\sim 3$ kpc from the center of the lens. In either case, it is reasonable to assume that the rotational velocity of the lensing galaxy has reached a relatively constant value at the projected location of both the southwest and northeast cores; $V(R) \approx V_0$. The observed velocity difference between two points in the galaxy is then

$$\Delta V_{\text{obs}} = V_0 (\cos \theta_1 - \cos \theta_2) \sin i,$$

where $\theta_i$ is the angle between the line of nodes and the line joining the center of the lens with the point where the line of sight crosses the disk, measured east of north.

The angles $\theta_i$ are $52^\circ$ and $204^\circ$ for the northeast and southwest components, respectively. This gives a simple relation between the maximum velocity $V_0$, the inclination $i$, and the observed velocity separation of the absorption lines: $|\Delta V| = V_0 (1.5 \cos \psi + 1.2 \sin \psi) \sin i$, where $\psi$ is the position angle of the major axis of the lensing galaxy. Geometrical considerations of the lensing morphology imply that the position angle is either $\sim 0^\circ$ or $\sim 90^\circ$ (Kochanek & Narayan 1992; Nair et al. 1993). The mass inside a radius $R$ is given by the virial theorem,

$$M(<R) \approx \frac{\Delta V^2 R}{\beta^2 G \sin^2 i} \approx \frac{7 \times 10^9}{\sin^2 i} M_\odot,$$

where $\beta$ is a factor depending on the position angle of the lens: $\beta = 1.5$ for $\psi = 0^\circ$ and $\beta = 1.2$ for $\psi = 90^\circ$. We will adopt a position angle $\psi = 0^\circ$ in the following discussion, keeping in mind that values can change by at most 20% should the position angle be $90^\circ$. In the last equation, we used $\Delta V = 147$ km s$^{-1}$ and $R = 3$ kpc.

The two radio components in PKS 1830–211 have almost identical substructure, suggesting that the components are two parity-reversed images of the background quasar caused by a nearly perfect alignment of the lens and the source (e.g., Nair et al. 1993). The separation of the northeast and southwest images can therefore be described as the effect of a single-point mass deflector of mass $M$, with the image separation given by the Einstein angle $\Delta \theta_E$,

$$\Delta \theta_E = 4 \sqrt{\frac{GM}{c^2D}} \approx 5.7 \times 10^{-6} \frac{M}{D} \text{arcsec}.$$

In the above equation, $M$ is expressed in solar mass and the distance parameter $D$ in Gpc; $D = D_L D_o / D_M$, where $D_L$ is the distance between the observer and the lens, $D_o$ the distance between observer and the source, and $D_M$ is the distance between the lens and the source, all measured as angular size distances (e.g., Schneider, Ehlers, & Falco 1992). The last equation yields

$$M \approx 3 \times 10^{10} D M_\odot$$

($D$ in Gpc) and, with the virial theorem,

$$V_0 \approx 220 \sqrt{D} \text{ km s}^{-1}.$$

In Figure 6 we plot $D$ as a function of the source redshift for a fixed lens redshift of $z = 0.88582$. The distances are derived using $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and for $q_0 = 0.5$ (solid line) and $q_0 = 0.05$ (dotted line). $D$ remains larger than 2 for all source redshift less than $z \approx 7$. This, together with
the last equation, means that the observed image separation of \( \sim 1'' \) already requires a massive galaxy for the lens; for a redshift of the background source \( z \geq 3 \), the required rotational velocity is 350 km s\(^{-1}\), corresponding to a massive early-type spiral. Lower redshifts for the background source would require higher rotational velocities, corresponding to an even more massive galaxy, which is not realistic for spirals (unless several galaxies are assumed to contribute to the lensing). Rotational velocities typical for late-type spirals can be excluded, since the redshift of the background source becomes forbiddingly large. Now, the relation \[ \Delta V = 1.5V_0 \sin i \] derived above, with \( \Delta V = 147 \text{ km s}^{-1} \) and \( V_0 = 350 \text{ km s}^{-1} \), yields an inclination of \( i = 16^\circ \).

How sensitively do these conclusions depend on the assumptions? (1) The approximation of the lensing mass as a singular point mass is only correct to first order if the lens and the background source are aligned. This is approximately true for PKS 1830–211. (2) The derivation of inclination assumes that the absorbing gas is in circular orbits. If it has noncircular motion with an amplitude comparable to the rotational velocity, this simple approach is not valid. However, the lens model of Kochanek & Narayan (1992) independently finds a low inclination. (3) The presence of an absorber at \( z = 0.193 \) introduces extra shear and, possibly, convergence of the ray bundles. However, given the relatively simple image configuration, it is not likely that the extra mass concentration at low redshift adds to the image multiplicity. It may, however, influence the interpretation of time-delay measurements, and Garrett et al. (1996) find from VLBI observations that the northeast core component has a more extended and complex morphology than the southwest component, which could be caused by the extra mass at \( z = 0.193 \). Hence, our results for the mass of the lens at \( z = 0.886 \) and the lower limit to the redshift of the source are quite robust, and we can make the following postulates:

1. The lensing galaxy is an early-type spiral galaxy seen at a low inclination (\( i < 20^\circ \)).
2. The mass within a radius of \( \sim 3 \text{ kpc} \) is in the range \( \sim 6–9 \times 10^{10} M_\odot \), which is similar, within a factor 2, to the Milky Way.
3. The redshift of the background source is large, most likely \( z_s > 3 \).

4.2. The Covering Factor of the Southwest Component

Frye et al. (1997) observed PKS 1830–211 with the BIMA millimeter array and found HCO\(^+\) (2 \( \leftarrow 1 \)) absorption only over the southwest component, as we do. However, the absorption line over this region did not reach zero level, indicating a filling factor of 70%–80%. This would mean that the prospect of using single-dish instruments to monitor the continuum and depth of saturated absorption lines with the aim of deriving the time delay between the northeast and southwest components could lead to ambiguities.

However, interferometric imaging of an object at low elevations is difficult in the millimeter band, and it is not clear how the accuracy of the interferometer data can be assessed. The flux ratio between the northeast and southwest continuum components in the BIMA data is 1.14 \( \pm \) 0.05 (Frye et al. 1997),\(^2\) compatible with our value at the same epoch, but their total flux is much higher than we find with either the Plateau de Bure, the IRAM 30 m, or SEST. In any case, the covering factor is quite high, almost 1 for our measurements (see Table 1), and is also compatible within 1 for the data of Frye et al. (1997) when their noise level is taken into account or if their continuum level is overestimated by a factor of \( \sim 1.4 \).

We do not think that this is the main uncertainty in the time-delay determination, the major uncertainty being the continuum level measurement.

It is not unexpected that a molecular cloud entirely covers one of the PKS 1830–211 images. The angular extent of the continuum emission region in the millimeter regime is not well known. The southwest image remains unresolved in 15 GHz VLBA observations (Garrett et al. 1996) at a resolution of \( 0.6 \times 0.2 \text{ mas} \). The northeast component, however, is resolved with a complex structure. An angular extent of 0.2 mas corresponds to \( \sim 1.1 \text{ pc} \), but the size of the continuum source at millimeter wavelengths could be considerably smaller. Millimeter VLBI of the BL Lac 3C 446 found an upper limit to the angular extent of 30 \( \mu \text{as} \) (Lerner et al. 1993).

In Figure 7 we show the spectrum of the HCO\(^+\) (2 \( \leftarrow 1 \)) absorption obtained with the Plateau de Bure interferometer with a velocity resolution of 0.5 km s\(^{-1}\). The profile is asymmetric, with an extension toward negative velocities. This part of the profile either is optically thin or has a covering factor less than the narrow component. Saturated absorption lines of a finite width should be flat bottomed when viewed with a high velocity resolution. The bottom of the narrow profile shown in Figure 7 appears to be deeper at negative velocities than at positive. The effect shows up only at the 1%–2% level. However, a similar asymmetry is seen in the lower resolution HCO\(^+\) (2 \( \leftarrow 1 \)) spectra obtained from both the IRAM 30 m and SEST telescopes (Fig. 2).

\(^2\) Taking the quoted fluxes and errors from Frye et al. (1997), we get a flux ratio of \( 1.14 \pm 0.24 \).
This asymmetry could represent small differences in the covering factor of the saturated absorption, corresponding to linear dimensions of ~5% of the extent of the continuum source.

5. SUMMARY

We have reported further molecular lines in absorption toward PKS 1830−211, and in particular CO (4 ← 3), the first CO line. Molecular abundances are compatible with Milky Way values.

We have also carried out interferometric measurements at three different epochs, and found that the magnification ratio between the two images has decreased from 1.8 to 1.0 during one year. These measurements confirm that the main V = 0 absorbing component covers the southwest image. We report the detection of a second component at \( V = -147.5 \text{ km s}^{-1} \) that covers only the northeast image.

The presence of two absorption lines, one corresponding to the southwest image of the background source and the other to the northeast component, implies that the background radio source is situated at a redshift \( z \approx 3 \), consistent with the lensing galaxy being an early-type spiral seen almost face-on (\( i \lesssim 16^\circ \)). A first determination of the time delay as 44 ± 9 days has been reported by van Ommeren et al. (1995). Given the model dependence of this measurement, it will be quite useful to try other independent determinations at various frequencies. We confirm here that with the southwest component being nearly completely absorbed at 3 mm, single-dish measurements are rapid and effective for this experiment. It will, however, be necessary to confirm from time to time that the filling factor is still \( \approx 1 \) through interferometric measurement (although this has not varied in the past year).

The lens geometry could be made more complex by the presence of another galaxy on the line of sight, detected in H I absorption by Lovell et al. (1996) at \( z = 0.1927 \). We detect neither molecular absorption nor emission at this redshift; the galaxy might not be exactly aligned with the quasar, which would minimize its lensing effect. Alternatively, since the H I absorption is seen only toward the northeast image, and molecular absorption has now also been detected toward this component, this \( z = 0.1927 \) absorption could be reinterpreted as absorption of a heavier molecule at \( z = 0.88489 \), the measured molecular redshift toward this northeast component. Exactly coinciding with this frequency, we find the (7−1,0,7,6) transition of the PS molecule, in a low enough excitation state. This interpretation is not likely, however, because of the expected low abundance of PS in the ISM.

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