IRAM observations of JVAS/CLASS gravitational lenses

E. Xanthopoulos1, F. Combes2, T. Wiklind3

1 University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL, England
2 DEMIRM, Observatoire de Paris, 61 Av. de l’Observatoire, F-75014 Paris, France
3 Onsala Space Observatory, S-43992 Onsala, Sweden

ABSTRACT
We have searched for molecular absorption lines at millimeter wavelengths in eleven gravitational lens systems discovered in the JVAS/CLASS surveys of flat spectrum radio sources. Spectra of only one source 1030+074 were obtained in the 3-, 2- and 1.3-millimeter band at the frequencies corresponding to common molecular transitions of CO and HCO+ as continuum emission was not found in any of the other sources. We calculated upper limits to the column density in molecular absorption for 1030+074, using an excitation temperature of 15 K, to be \(N_{\text{CO}} < 6.3 \times 10^{13} \, \text{cm}^{-2}\) and \(N_{\text{HCO}^+} < 1.3 \times 10^{11} \, \text{cm}^{-2}\), equivalent to hydrogen column density of the order \(N_{\text{H}} < 10^{18} \, \text{cm}^{-2}\), assuming standard molecular abundances. We also present the best upper limits of the continuum at the lower frequency for the other 10 gravitational lenses.

Key words: cosmology: observations – gravitational lensing.

1 INTRODUCTION
Molecular gas, the cold and dense part of the interstellar medium (ISM) is directly related to the formation of stars. When studied at high redshifts, it can give us some insight into the evolution of star formation conditions. The problem of galaxy evolution is directly related to the study of star forming activity and gas content of distant galaxies. However, given the present-day size and technology of millimeter and centimeter radio telescopes, even very luminous galaxies are exceedingly difficult to detect at large distances. The current sensitivity of radio telescopes is at least an order of magnitude below what would be needed to determine the molecular content of high redshift spirals. This order of magnitude is what is gained by observing gravitational lensed objects with single dish radio telescopes since magnification “boosts” the flux of the sources that would otherwise be too faint to be studied.

CO emission has been detected in a number of gravitationally lensed systems (Brown & Vanden Bout 1991, Barvainis et al. 1994, Casoli et al. 1996, Alloin et al. 1997, Barvainis et al. 1998). In 1997, Scoville et al. reported the detection of the first non-lensed object at \(z=2.394\) and Guilloteau et al. (1997) of the first radio-quiet quasar at \(z=4.407\) with no direct indication of lensing. More recently, Papadopoulos et al. (2000) reported the detection of submillimeter emission from dust at 850 \(\mu\)m and of the CO(4-3) line in two high redshift powerful radio galaxies (see also Combes (1999) for a review of molecular studies of high redshift objects).

Absorption molecular lines are much easier to detect, especially at large distances, since for their detection the sensitivity depends on the strength of the background continuum source and not on the distance. This has been demonstrated by the detection of more than 40 different molecular transitions at redshifts ranging from \(z=0.25\) to \(z=0.89\) (Wiklind & Combes, 1994, 1996a, 1996b; Combes & Wiklind 1995). Just as in the optical wavelength band, it is easier to detect molecular absorption lines (at mm wavelengths) than the corresponding emission lines. With an appropriate alignment of an intervening galaxy and a sufficiently strong background radio continuum source, it is possible to probe the molecular ISM at very large distances. Absorption of molecular rotational lines in the millimeter band is then a very sensitive method of studying the physical and chemical conditions of molecular gas at large distances. Also due to the greater sensitivity of the absorption lines, it is possible to observe molecules other than CO. These types of surveys can then provide us with valuable information about the classification of lenses (see for example Wiklind and Combes (1995) and their study of the gravitational lens system B0218+357).

The probability of detecting molecular absorption lines is larger when the impact parameter between the background source and the intervening galaxy is very small, as is the case in gravitational lens systems. In fact, Wiklind and Combes (1995, 1996) have shown that it is feasible to measure the redshift of the lensing object by mm-wave spectroscopy. This method is extremely promising to provide the much needed redshifts that will exploit the potential of grav-
Table 1. General characteristics of the JVAS/CLASS gravitational lenses in the sample

| Source No. | Source images | Lens redshift $z_l$ | Max. separ. | V | Magnitude | Refer. |
|------------|---------------|--------------------|-------------|---|------------|--------|
| CLASS0712+472 | 4 | 1.34 | 0.406 | 1.27 | 22.4 | 20.0 | 17.7 |
| CLASS0827+525? | 2 | (2.064) | 2.85 | 1.56 | 22.7 | 20.4 | (2) |
| JVAS1030+074 | 2 | 1.53 | 0.599 | 1.56 | 22.4 | 22.5 | (3) |
| CLASS1127+385 | 2 | 0.701 | 2.08 | 1.28 | 21.4 | (4) |
| JVAS1422+231 | 4 | 3.62 | 0.34 | 2.08 | 19.0 | (5) |
| CLASS1600+434 | 2 | 1.57 | 0.415 | 1.39 | 23.7 | 21.2 | 18.5 |
| CLASS1608+656 | 4 | 1.39 | 0.64 | 2.08 | 19.0 | (6) |
| CLASS1933+503 | 4+4+2 | (2.62) | 0.755 | 1.17 | <23.5 | 21.8 | 18.6 |
| JVAS1938+666 | 4+2 | (0.878) | 0.93 | 18.5 | (7) |
| CLASS2045+265 | 4 | 1.28 | 0.87 | 1.86 | 20.4 | (8) |
| JVAS2114+022 | 2 | 0.315 | 2.57 | 17.0 | 17.2 | (9) |

(1) Jackson et al. (1998)
(2) Koopmans et al. (2000)
(3) Xanthopoulos et al. (1998)
(4) Koopmans et al. (1999)
(5) Patnaik et al. (1992a)
(6) Jackson et al. (1995)
(7) Myers et al. (1995)
(8) Sykes et al. (1998)
(9) Patnaik et al. (1992b); King et al. (1997)
(10) Fassnacht et al. (1999)
(11) King et al. (1999); Augusto et al. (2000, in preparation)

Table 2. Non-detection of absorption in 1030+074 – Upper limits at 3σ

| Transition | $\nu_{\text{obs}}$ (GHz) | $T_{\text{cont}}$ (mK) | $\delta \nu$ (km s$^{-1}$) | $\sigma_{\text{rms}}$ (mK) | $\int T_{\nu} d\nu$ (km s$^{-1}$) | $N_{\text{tot}}$ (cm$^{-2}$) |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| HCO+(2-1)  | 111.5           | 41              | 2.7             | 2               | 0.4             | $<1.3 \times 10^{11}$ |
| CO(2-1)    | 144.2           | 34              | 2.7             | 2               | 0.5             | $<6.3 \times 10^{13}$ |
| CO(3-2)    | 216.3           | 15              | 2.7             | 3               | 2.4             | |

Table 3. 1030+074: The centimeter and millimeter fluxes

| Frequency (GHz) | Flux (mJy) |
|-----------------|------------|
| 0.365           | 199 ± 9.0  |
| 1.4             | 155 ± 4.0  |
| 4.85            | 341 ± 5.0  |
| 8.4             | 203 ± 0.3  |
| 111.5           | 246 ± 12   |
| 144.2           | 255 ± 12   |
| 216.3           | 144 ± 10   |

Gravitational lenses as powerful constraints on cosmology and galactic structure (e.g. Kochanek 1996; Keeton et al. 1998; Falco et al. 1998; Helbig, et al. 1999). Since we also have multiple lines of sight, this type of surveys gives us the possibility of useful kinematical information.

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 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 Jodrell-Bank VLA Astrometric Survey (JVAS; Patnaik et al. 1992a; Patnaik 1993; Browne et al. 1998, Wilkinson et al. 1998; King et al. 1999) and the Cosmic Lens All Sky Survey (CLASS; Browne et al. 1999; Myers et al. 1999) are surveys of flat-spectrum radio sources one of whose purposes is to search for gravitational lens systems. Nineteen new lenses have been uncovered up to now. In this paper we present the results of submillimeter observations of 11 of these lens systems. We did not detect absorption in any of the sources and continuum was found in only the lens system 1030+074. In Section 2 we describe the observations and in Section 3 we derive upper limits to the molecular absorption column densities in 1030+074 and upper limits to the continuum emission of the rest of the sources. A discussion follows in Section 4.
2 OBSERVATIONS

The observations were made with the Institut de Radio Astronomie Millimétrique (IRAM) 30-m telescope at Pico Veleta, Granada, Spain in 1997 December. Table 1 shows the main characteristics of the lenses in the sample. In column 1 we give the JVAS/CLASS name of the source and in columns 2, 3, 4 and 5 we present the number of components in each system, the source and lens redshift, when available (we have put in a parenthesis the redshifts that were unknown at the time of the observations), and the maximum separation between the components of each system respectively. In columns 6, 7, and 8, one can find the HST/WFPC2 V and I and HST/NICMOS H magnitudes (Impey et al. 1996; King et al. 1998; Marlow et al. 1999; Jackson et al. 2000; and references in Table 1) of the lensing galaxy. The discovery paper reference of each system is given in the last column of the table. We used the 3, 2 and 1.3 mm SIS receivers. The observations were done with a nutating subreflector with a frequency of 0.5 Hz and with a throw of ±90° in azimuth. We used a frequency resolution of 1 MHz, which corresponds to a velocity resolution of 2.7 km s⁻¹ at 3-mm. The continuum levels of the observed sources were determined using a continuum backend and increasing the subreflector switch frequency to 2 Hz. Since none of the 11 systems/sources had a known continuum millimeter flux we decided to do the following: for the three lenses in the sample for which we already had a confirmed redshift and were known to have a strong continuum three lenses in the sample for which we already had a continuum backend and increasing the subreflector switch frequency to 2 Hz. We also present in Table 1 a collection of all the radio fluxes available for these systems from the Texas, NVSS, GB6, WENSS (Rengelink et al. 1997) and other published in the literature. In the last column we also note whether variability was detected or not in these sources. Most of the radio information come from the discovery papers that can be found in the last column of Table 1.

3 RESULTS – ANALYSIS OF ABSORPTION LIMITS

3.1 Molecular absorption upper limits

We have used the non-detection of absorption in 1030+074 to place upper limits on the column density in the various molecules. The calculations were made in the same way as in Wilklin & Combes (1996b), based on the noise in a single spectral element, 1 MHz channels (2.7 km sec⁻¹ channels), and the results for 1030+074 are shown in Table 1. We have assumed an excitation temperature of 15 K. In column 1 we have the molecular line, in column 2 the observed frequency and in column 3 the measured continuum temperature. In columns 4 and 5 one can find the spectral element and the noise level for each observation. In column 6 we calculate an integrated optical depth \( \int \tau d\nu \) using the formula

\[
\tau = -\ln(1 - 3\sigma_{\text{rms}}/T_{\text{cont}}).
\]

Finally, the upper limits to the column densities for the two molecular species are presented in the last column. The derived upper limit of the absorption is \( N_{\text{CO}} < 6.3 \times 10^{13} \text{ cm}^{-2} \). This value is much lower than the typical value of \( 10^{15} - 10^{16} \text{ cm}^{-2} \) for molecular gas in a variety of different environments, both in our own and nearby galaxies. For the \( N_{\text{HCO}^+} \) we find \( < 1.3 \times 10^{15} \text{ cm}^{-2} \) at 3\( \sigma \). If we assume standard molecular abundances then we find that the hydrogen column density at the 3\( \sigma \) level is \( N_H < 10^{15} \text{ cm}^{-2} \).

We convert the values found for the continuum emission of 1030+074 to mJy by using the conversion factor, the flux density to antenna temperature ratio \( S/T_A \) for a point source. These values are 6.0, 7.5 and 9.6 Jy/K for the 3, 2, and 1.3 mm receivers respectively. So the continuum emission values that we get for 1030+074 are 246, 255, and 144 mJy at the three frequencies respectively. In Table 2 we combine our own continuum data with those of lower frequencies available for 1030+074. The lower frequency 0.365 GHz, 1.4 GHz and 4.85 GHz flux densities were obtained from the Texas (Douglas et al. 1996), NVSS (Condon et al. 1998) and GB6 (Gregory et al. 1996) catalogues/surveys and are 199 mJy, 155 mJy and 341 mJy respectively. The 8.4 GHz flux density of 203.3 mJy was obtained from the CLASS VLA data. Table 2 gives a further indication that 1030+074 is a system with strong variability (Xanthopoulos et al. 2000, in preparation) and so a source suitable for \( H_0 \) determination.

For the other 10 lens systems for which we did not detect continuum emission, within 15 min of observing time on each source, we present in Table 2 the best upper limit in mK and mJy at the lower 3-mm frequency.

We also present in Table 2 a collection of all the radio fluxes available for these systems from the Texas, NVSS, GB6, WENSS (Rengelink et al. 1997) and other published in the literature. In the last column we also note whether variability was detected or not in these sources. Most of the radio information come from the discovery papers that can be found in the last column of Table 1.

3.2 Optical absorption

The lens system 1030+074 has been observed with the HST WFPC2 and NICMOS at V, I and H (Jackson et al. 2000). Falco et al. (1999) have determined the total \( E(B-V) \) extinction for this lens system to be 0.38±0.18 which we use to convert to a hydrogen column density. For this conversion we use the Bohlin et al. (1978) relation that gives the mean ratio of the total neutral hydrogen to the color excess, that is:

\[
N(H) = (E(B-V))/2.2 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1} \text{ for the Solar neighbourhood.}
\]

This relationship gives

\[
N_H \approx 2.2 \times 10^{21} \text{ cm}^{-2}.
\]

So if all the reddening is dust at the lens redshift, then we have a hydrogen column density which is 3 orders of magnitude larger that the upper limit implied by the molecular absorption data. One possible explanation might be that the total extinction is associated with the source rather than...
\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure1}
\caption{\(\Delta v = 2.7 \text{ km s}^{-1}\) spectra of CO (J = 2–1), CO (J = 3–2) and HCO\(^+\) (J = 2–1) at 1030+074. The velocity scale is heliocentric and centered at \(z=0.599\).}
\end{figure}

The non-detection of continuum in 10 of the 11 lens systems that we observed shows that they are weaker at mm wavelengths than at radio wavelengths. This is not entirely unexpected since the sources were selected to have flat spectral indices \((\alpha > -0.5, \propto \nu^{\alpha})\) between 1.4 and 5 GHz. As can be seen from Table 5, however, a lot of the sources in our sample show quite a steep decrease in their continuum flux at 8.4 GHz. Also, the spectral index contains an uncertainty from the fact that many of the selected sources are variable. The only source that actually seems to have a strong enough continuum, and despite known variability with frequency up to 20-30\% (Xanthopoulos et al. 1998) and signs of variability with time maybe up to 30-40\% (Xanthopoulos et al. in
ACKNOWLEDGMENTS

We would like to thank our referee Lindsay King for many useful comments. This research was supported by European Commission, TMR Programme, Research Network Contract ERBFMRXCT96-0034 “CERES”.

REFERENCES

Alloin, D., Guilloteau, S., Barvainis, R., Antonucci, R., Tacconi, L., 1997, A&A, 321, 24
Barvainis, R., Tacconi, L., Antonucci, R., Alloin, D., Coleman, P., 1994, Nature 371, 586
Barvainis, R., Alloin, D., Guilloteau, S., Antonucci, R., 1998, ApJ, 429, L13
Bohlin, R. C., Savage, B. D., Drake, J. F., 1978, ApJ, 224, 132
Brown, R. L., Vanden Bout, P. A., 1991, AJ, 102, 1956
Browne, I. W. A., Patnaik, A. R., Wilkinson, P. N., Wrobel, J. B., 1998, MNRAS, 293, 257
Browne, I. W. A., et al. 1999, to appear in the “Gravitational Lensing: Recent Progress and Future Goals”, eds. T. Brainerd and C. Kochanek
Casoli F., Encrenaz, P., Fort, B., Boise, P., Mellier, Y., 1996, A&A, 306, L41
Combes, F., 1999, astro-ph/9909016
Combes, F., Wikhind, T., 1995, A&A, 299, 382
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., Broderick, J. J, 1998, AJ, 115, 1693
Douglas, J. N., Bash, F. N., Bozyan, F. A., TORRENS, G. W., Wolfe, C. 1996, AJ, 111, 1495
Falco, E. E., Lehár, J., Shapiro, I. I., 1997, AJ, 113, 540
Falco, E. E., Kochanek, C. S., Muñoz, J. A., 1998, ApJ, 494, 47
Falco, E. E., Impey, C. D., Kochanek, C. S., Lehár, J., McLeod, B. A., Rix, H.-W., Keeton, C. R., Muhöf, J. A., Peng, C. Y., 1999, ApJ, 523, 617
Fassnacht, C. D., Cohen, J. G., 1998, AJ, 115, 377
Fassnacht, C. D., et al. 1999, AJ, 117, 658
Gregory, P. C., et al. 1996, ApJS, 103, 427
Guilloteau, S., Omont, A., McMahon, R. G., Cox, P., PetitJean, P., 1997, A&A, 328, L1
Helbig, P., Marlow, D., Quast, R., Wilkinson, P. N., Browne, I. W. A., Koopmans, L. V. E., 1999, A&AS, 136, 297
Impey, C. D., Foltz, C. B., Petry, C. E., Browne, I. W. A., Patnaik, A. R., 1996, ApJ, 462, L53
Jackson, N., et al., 1995, MNRAS, 274, L25
Jackson, N., et al., 1998, MNRAS, 296, 483
Jackson, N., et al., 1999, MNRAS, 307, 225

Table 5. Radio information of the lens systems in our sample.

| Source | Radio fluxes (mJy) | Variability |
|--------|-------------------|-------------|
|        | 0.325 GHz | 0.365 GHz | 1.4 GHz | 4.85 GHz | 8.4 GHz | 15 GHz |
| 0712+472 | 41 | – | 25 | 30 | 26.6 | – | yes |
| 0827+525 | 71 | – | 72 | 47 | 28.0 | 37.1 | yes |
| 1127+385 | 12 | – | 29.3 | 15.3 | 14.7 | no |
| 1422+231 | – | – | 268 | 548 | 152.8 | – | yes |
| 1600+434 | 37 | – | 76.4 | 37 | 132 | yes |
| 1608+656 | 228 | – | 67 | 88 | 35.1 | – | yes |
| 1933+503 | 310 | – | 108 | 63 | 17.6 | – | no |
| 1938+666 | 753 | 681 | 576 | 329 | 169.9 | – | ? |
| 2045+265 | – | 55 | 55 | 18.2 | – | ? |
| 2114+022 | – | 137 | 224 | 43.4 | – | ? |
Koopmans, L. V. E., et al. 1999, MNRAS, 303, 727
Koopmans, L. V. E., et al. 2000, A&A, 361, 815
Kochanek, C. S., 1996, ApJ, 466, 638
Marlow, D. R., Browne, I. W. A., Jackson, N., Wilkinson, P. N., 1999, MNRAS, 305, 15
Myers, S. T., et al., 1995, ApJ, 447, 5
Myers, S. T., et al., 1999, to appear in the “Gravitational Lensing: Recent Progress and Future Goals”, eds. T. Brainerd and C. Kochanek
Papadopoulos, P. P., Röttgering, H. J. A., van der Werf, P. P., Guilloteau, S., Omont, A., van Breugel, W. J. M., Tilanus, R. P. J., 2000, ApJ, 526, 626
Patnaik, A. R., Browne, I. W. A., Wilkinson, P. N., Wrobel, J. M., 1992a, MNRAS, 254, 655
Patnaik, A. R., Browne, I. W. A., Walsh, D., Chaffee, F. H., and Foltz, C. B., 1992b, MNRAS, 259, 1P
Patnaik, A. R., 1993, Proceedings of the 31st Liège International Astrophysical Colloquium “Gravitational Lenses in the Universe”, p. 311
Rengelink, R. B., Tang, Y., de Bruyn, A. G., Miley, G. K., Bremer, M. N., Roettgering, H. J. A., Bremer, M. A. R., 1997, A&AS, 124, 259
Scoville, N. Z., Yun, M. S., Windhorst, R. A., Keel, W. C., Armus, L., 1997, ApJ, 485, L21
Sykes, C. M., et al., 1998, MNRAS, 301, 310
Wiklind, T., Combes, F., 1994, A&A, 286, L9
Wiklind, T., Combes, F., 1995, A&A, 299, 382
Wiklind, T., Combes, F., 1996, The Messenger No. 84, 23
Wiklind, T., Combes, F., 1996a, Nature, 379, 139
Wiklind, T., Combes, F., 1996b, A&A, 315, 86
Wilkinson, P. N., Browne, I. W. A., Patnaik, A. R., Wrobel, J. M., Sorathia, B., 1998, MNRAS, 300, 790
Xanthopoulos, E., Browne, I. W. B., King, L. J., Koopmans, L. V. E., Jackson, N. J., Marlow, D. R., Patnaik, A. R., Porcas, R. W., Wilkinson, P. N., 1998, MNRAS, 300, 649.

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