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THE MOLECULAR MEDIUM OF H1413+117: BIMA CO (3–2) AND HCO^+ (4–3) OBSERVATIONS

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ABSTRACT

We report observations of the CO (3–2) and HCO^+ (4–3) lines toward H1413+117, the $z = 2.56$ "cloverleaf" quasar, obtained simultaneously with the BIMA. These observations, with beam size 2″.8 × 2″.4, confirm the CO (3–2) emission redshifted to 3 mm wavelength observed at lower resolution by Barvainis and coworkers. We find an upper limit to the HCO^+ (4–3)/CO (3–2) intensity ratio of 0.33. This suggests that the mean density of the molecular gas, averaged over the beam, is lower than the 10^7 cm^{-3} "critical density" of the HCO^+ (4–3) line for collisional excitation. The implications of this limit depend primarily on the size scale probed by the observations. The physical conditions appear generally consistent with an average over molecular complexes in the central kiloparsecs of nearby starburst galaxies but may differ from those in the inner 300 pc of NGC 1068, the active nucleus with the best studied molecular medium.

The technique of simultaneous line observation at millimeter wavelengths, which minimizes relative calibration uncertainties, is especially valuable for the broad, weak lines from high-redshift objects for which accurate absolute calibration is troublesome. We note several diagnostic molecular line pairs, redshifted into the 3 mm band, accessible to simultaneous measurement with the present generation of millimeter interferometers.

Subject headings: galaxies: ISM — gravitational lensing — ISM: molecules

1. INTRODUCTION

The detections of CO line and dust continuum emission from the $z = 2.3$ *IRAS* galaxy IRAS F10214+4724 (Brown & Vanden Bout 1991; Downes et al. 1992) and the $z = 2.5$ H1413+117 "cloverleaf" quasar (Barvainis, Antonucci, & Coleman 1992; Barvainis et al. 1994) have opened up the realm of high-redshift galaxies to millimeter astronomy. While both of these objects appear to be gravitationally lensed, which likely accounts for their exceptionally bright emission, observations of the molecular gas in these systems can provide potentially important glimpses into starburst/active nucleus processes in the early universe. For example, it remains unclear whether the primary power in these objects is provided by a starburst or an active nucleus, or whether there exists an evolutionary connection between these phenomena.

Most observations of molecular gas at high redshift focus on the low-*J* rotational transitions of CO. These transitions are excited at relatively low densities and temperatures, and therefore are likely to trace the bulk of the molecular material. However, direct estimates of the properties of the molecular gas from CO observations are made difficult by both the problems inherent in the conversion of CO luminosity to H_2 mass and the uncertainties associated with gravitational lensing in these systems. By contrast, observations of molecular lines from trace molecular species with a wide range of excitation requirements provide an alternative means of probing the molecular material directly. Measurements of line ratios are especially valuable in this context. Moreover, if observations of two or more lines can be obtained with the same instrument, and, even better, at the same time, relative calibration uncertainties can be minimized.

Of particular interest is the fraction of dense molecular gas present in these systems. A zero-order estimate of this quantity may be obtained by comparing emission from CO and from a high dipole moment molecule, such as HCN, HCO^+, or CS, that requires densities two or more orders of magnitude higher for collisional excitation. In a sample of ultraluminous far-IR galaxies, Solomon, Downes, & Radford (1992a) find remarkably bright emission from high dipole moment species. The typical HCN (1–0)/CO (1–0) intensity ratio in these systems is 0.15; this suggests large masses of dense molecular gas engaged in star formation and supports a starburst origin for the enhanced far-IR luminosity. In more extreme molecular environments, even higher HCN/CO ratios have been found. Jackson et al. (1993), using the Nobeyama interferometer, observed the HCN (1–0)/CO (1–0) intensity ratio to be enhanced to nearly unity in the nucleus of the nearby starburst/active galaxy hybrid NGC 1068, as compared to a value 50 times lower in the inner disk. Similar results have been obtained in higher resolution studies of NGC 1068 with the Berkeley-Illinois-Maryland Array (BIMA) and Plateau de Bure array (see Helfer & Blitz 1995 for a summary). Molecular lines with even more stringent excitation requirements have also been found to be bright in the nucleus of NGC 1068, for example, the HCN (4–3) line observed by Tacconi et al. (1994). Taken together, these data suggest the presence of a high-density molecular component in the center of NGC 1068, with morphology and kinematics consistent with a 300 pc molecular torus that obscures the Seyfert nucleus.

In this Letter, we report BIMA observations of the CO (3–2) and HCO^+ (4–3) lines toward H1413+117, redshifted to 3 mm wavelength. These observations confirm the CO (3–2) emission detected by Barvainis et al. (1994), obtain higher angular resolution, and explore the simultaneous measurement of emission from CO and from a high dipole moment species that distinguishes the presence of dense molecular gas.

2. OBSERVATIONS

H1413+117 was observed with three configurations of the six antenna BIMA in 1995 February, March, and May. The

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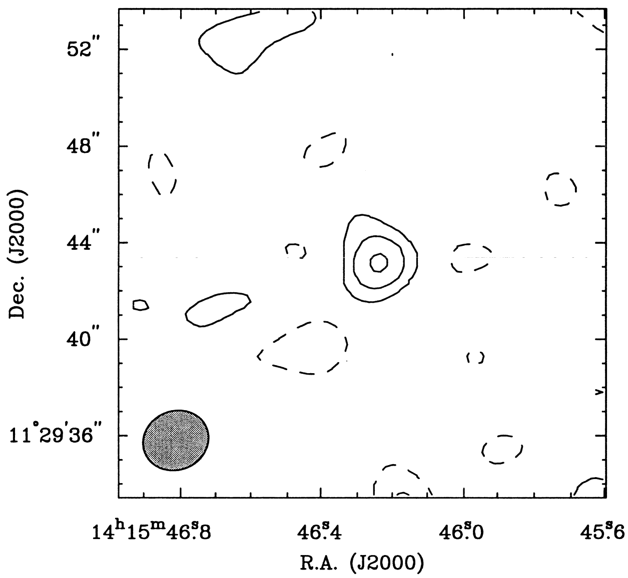

FIG. 1.—Integrated intensity map of the CO (3–2) emission from H1413+117. The lowest contour and interval are 13 mJy $beam^{-1}$. Negative contours are dashed. The 2″8 × 2″4 beam is illustrated in the lower left-hand corner. The emission is unresolved.

phase center was α(J2000) = $14^h15^m46^s.27$, δ(J2000) = 11°29′43″8. Projected baselines ranged from 6 to 215 m. The instrumental gain and passband were calibrated with observations of the nearby bright quasar 3C 273 obtained approximately every 30 minutes. The absolute flux density scale was referenced to 3C 273, which was calibrated against planets from time to time during the period of the observations and should be accurate to 20%.

The digital correlator was configured with eight partially overlapping windows, each with 32 channels spanning 100 MHz bandwidth. These windows covered the CO (3–2) line (345.795989 GHz, redshifted to 97.13398 GHz) and the HCO^+ (4–3) line (354.5054759 GHz, redshifted to 100.20654 GHz) in the upper and lower sidebands of the first local oscillator, respectively. Since the second local oscillator frequency is fixed at 1270 MHz and the intermediate frequency (IF) band is limited to 70–900 MHz, it was not possible to center both molecular lines within the band to obtain identical velocity coverage. As a compromise, we set the center frequency to maximize the bandwidth to the low edge of the IF band for both lines. This resulted in velocity coverage at $z = 2.56$ of −600 to 850 km s^{-1} for the CO (3–2) line and −825 to 575 km s^{-1} for the HCO^+ (4–3) line.

The MIRIAD package was used for calibration and mapping. For each line, the visibilities were averaged into 14 bins of width 100 km s^{-1} and Fourier transformed, using natural weighting for maximum sensitivity. The resulting CO (3–2) and HCO^+ (4–3) maps were cleaned to the rms noise level (11 mJy $beam^{-1}$) and restored with a FWHM Gaussian beam 4″4 × 3″5 at p.a. −56°. An additional set of maps was made excluding data from projected baselines shorter than 70 m; this resulted in a smaller beam, 2″8 × 2″4 at p.a. −67°, at the expense of increased noise (17 mJy $beam^{-1}$).

3. RESULTS

The CO (3–2) emission from H1413+117 was clearly detected but not spatially resolved. Figure 1 shows the central part of the high-resolution CO (3–2) image, integrated over the velocity range −350 to 50 km s^{-1}. The peak emission is offset (−0″4, −0″5) from the field center, with an estimated error of 0″2, which is dominated by the uncertainty in the baseline determination and the relatively large distance (26°) between the source and the calibrator. Figure 2 shows the CO (3–2) and HCO^+ (4–3) spectra derived from maps made with the full data set. A Gaussian fit to the CO (3–2) spectrum gives peak flux density 41 ± 8 mJy, velocity −178 ± 35 km s^{-1}, and FWHM line width 352 ± 81 km s^{-1} (uncorrected for the channel width). Thus the CO location, size, peak flux, central velocity, and line width are all consistent with the IRAM observations of Barvainis et al. (1994). No additional significant emission features were detected in the larger ~2′ field of view of the BIMA antennas.

The HCO^+ (4–3) line was not detected above the noise level. To place an upper limit, we assume the HCO^+ (4–3) line-center velocity and width are the same as those found for the CO (3–2) line. This is a reasonable assumption, based on the observed line profiles of high-density tracers in the local

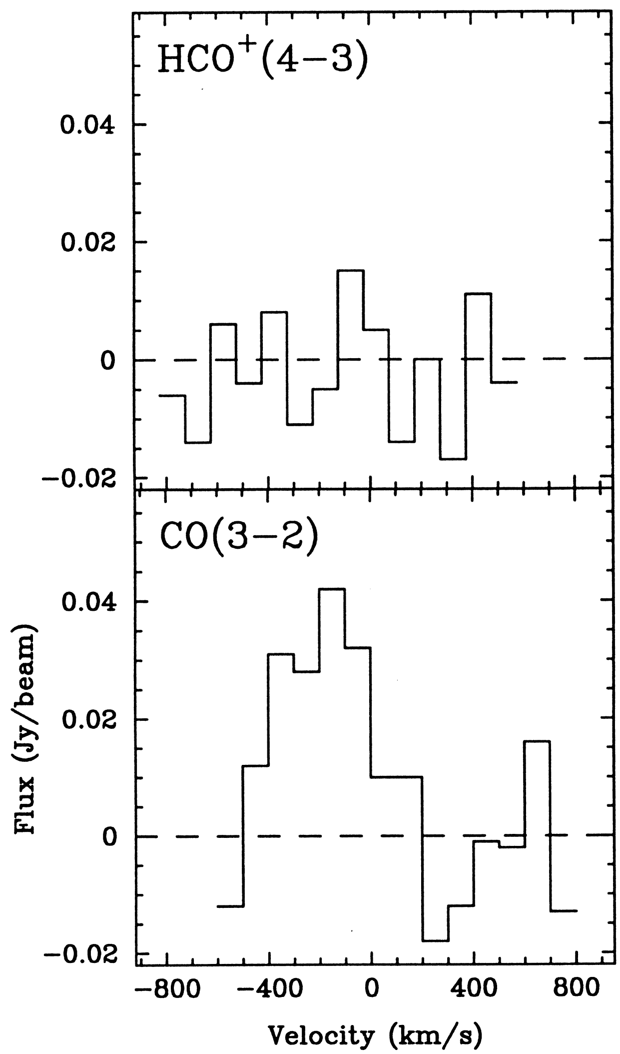

FIG. 2.—Spectra of the HCO^+ (4–3) (*top*) and CO (3–2) (*bottom*) lines derived from maps made with the full set of visibility data (synthesized beam 4″4 × 3″5 at p.a. −56°), smoothed to a resolution of 100 km s^{-1}. The velocity scale assumes $z = 2.56$.

extragalactic environment. We also assume the HCO^+ (4–3) line emission is not brighter than twice the measured rms noise. This gives an upper limit of 0.33 to the HCO^+ (4–3)/CO (3–2) integrated intensity ratio. This ratio is largely free of relative calibration errors, as the lines were observed at the same time.

4. DISCUSSION

A definitive interpretation of the HCO^+ (4–3) line and CO (3–2) line observations of H1413+117 is rendered problematic by several factors. The primary difficulty is the poor angular resolution that leaves unresolved the basic source structure and the effects of gravitational lensing. A second difficulty is that straightforward empirical comparisons with observations of more nearby systems are hampered by a lack of similar submillimeter-wavelength data. A third problem is the poorly understood chemistry of the trace species. We consider these issues in more detail below and discuss the constraints on the molecular gas provided by the observations.

4.1. *Molecular Gas Distribution*

Observations of objects at $z = 2.5$ with angular resolution $\gtrsim 1''$ necessarily average over size scales $\gtrsim 4\ h^{-1}$ kpc ($H_0 = 100\ h$ km s^{-1} Mpc^{-1}). Thus, the underlying morphology and inhomogeneities remain largely unresolved, and it is impossible to locate directly sources of molecular emission. For H1413+117, the CO emission appears pointlike in the $2\farcs8 \times 2\farcs4$ beam obtained in this study. A minimum source size can be estimated by comparing the observed brightness temperature to the intrinsic source brightness temperature, assuming simple beam dilution: $\theta_s'' = (2.8 \times 2.4)^{0.5}(0.75\ \mathrm{K})(1 + z)/T_B$, where 0.75 K is the observed CO (3–2) peak brightness and T_B is the intrinsic brightness temperature. The observed brightness is compatible with a source unresolved by the beam for $T_B \gtrsim 10$ K. The mention of detectable CO (7–6) emission from the source by Barvainis et al. (1994), a transition with an upper energy level 155 K above the ground state, suggests that the excitation conditions are unlike those in average Galactic molecular clouds, where emission from the CO (7–6) line arises only from warm, dense cores forming O and B stars. (Note that radiative excitation by the 9.8 K cosmic background at $z = 2.56$ does not significantly affect the $J = 7$ level.) If the molecular medium is warm and the CO (3–2) line optically thick, as is likely, then the intrinsic brightness temperature could be substantially larger than 10 K. This would imply the emission is clumped within the beam, a conclusion consistent with the subarcsecond structure apparent at optical wavelengths.

The problem of inadequate spatial resolution is underscored by the evolving understanding of the nature of the molecular emission from IRAS F10214+4724, whose millimeter-wave properties are similar to those of H1413+117. Early interpretations of the (unresolved) bright CO emission from IRAS F10214+4724 suggested that it was a primeval galaxy undergoing a starburst (e.g., Solomon, Downes, & Radford 1992b). However, recent high-resolution optical and near-IR observations instead imply that gravitational lensing is likely responsible for the unusually strong CO emission (Elston et al. 1994; Matthews et al. 1994; Graham & Liu 1995). The lens models of Broadhurst & Lehar (1995) show that the molecular emission in this source may arise from a small (100 h^{-1} pc) region, perhaps a torus surrounding an active nucleus, magnified 50 times or more by virtue of a location projected on a lens caustic, though this interpretation is certainly not unique.

For H1413+117, the quadruple morphology of the optical images (the "cloverleaf"; Magain et al. 1988) suggests that the lens is well centered on the quasar. In this geometry, very high magnification of a small region associated with the optical light is not likely. Of course, the synthesized beam of the present study, while an order-of-magnitude improvement over earlier observations, is still much larger than the $\sim 1''$ Einstein ring diameter, and the molecular emission remains unresolved. Thus, the existence of a highly magnified molecular hot spot, similar to the "strong radio source" observed in this object at centimeter wavelengths (Kayser et al. 1990), cannot be ruled out. However, the CO emission centroid is observed to lie within the polygon formed by the optical images, and this symmetry would suggest the molecular emission is not dominated by a single hot spot substantially offset from the optical light. Most probably, the molecular emission arises from a kiloparsec size scale, perhaps a circumnuclear region of enhanced star formation triggered by a merger, as first suggested by Barvainis et al. (1994).

If the molecular gas density in H1413+117 were sufficiently high to ensure conditions close to LTE (a Boltzmann population distribution) in all species, assumed coextensive, then the CO (3–2) and HCO^+ (4–3) lines observed in this study would exhibit comparable brightness. However, the simultaneous observations of these two lines demonstrate conclusively that they are not close to equal brightness. From this, we can say the density of the bulk of the molecular gas cannot be higher than the critical density of the HCO^+ (4–3) line for collisional excitation, $n_{\mathrm{crit}} \sim 10^7$ cm^{-3}. This statement could be quantified more precisely by appealing to large velocity gradient models that take into account radiative trapping in a simple way (together with assumptions about column densities and temperatures), but such a detailed treatment is not warranted by the present data.

Unfortunately, submillimeter-wavelength observations of molecular lines in nearby galaxies are only just now beginning to reveal the physical conditions in molecular clouds involved in the starburst/active nucleus phenomena. The situation is analogous to that of early optical observations of high-redshift sources, where comparable ultraviolet observations (from space) of the same lines in nearby systems were few. In the prototypical starburst galaxies M82 and NGC 253, recent observations by Jackson et al. (1995) found large differences in submillimeter HCO^+ and HCN emission that imply an order-of-magnitude difference in mean density in these objects, despite their very similar CO and far-IR luminosities. There is some evidence from mapping these sources that the molecular gas is more dense closer to the nucleus, but it is not clear whether this is an intrinsic property of the starburst. An additional complication is introduced by the poorly understood chemistry of the trace species. In M82 and NGC 253, the HCN (4–3)/HCO^+ (4–3) intensity ratios determined by Jackson et al. (1995) are less than 0.4 and 0.9–1.5, respectively. In a more extensive sample of 15 galaxies, Nguyen-Q-Rieu et al. (1992) found that the HCN (1–0)/HCO^+ (1–0) ratio varied from 0.5 to 4, independent of any obvious measures of star formation. There is a tantalizing hint in the data that HCO^+ emission is enhanced in regions that might be rich in cosmic rays from supernova explosions, but this connection is far from firmly established. Thus, existing data on the best studied nearby systems provide little guidance as to which lines of which species, even among those with similar excitation requirements, provide useful diagnostics of starburst activity.

Nonetheless, neglecting the above complications, basic excitation considerations suggest that the comparison of HCO^+ (4–3) and CO (3–2) emission provides a reliable indication of the fraction of dense molecular gas, averaged over the beam. To what extent does this comparison constrain the nature of its molecular medium in H1413+117? Since molecular gas may fuel active nuclei as well as starbursts, the significance of the relative weakness of the HCO^+ (4–3) line as compared to the CO (3–2) line in H1413+117 depends critically on the size scale probed by the observations. If the data are sensitive to a region spanning kiloparsecs across the source, then the molecular properties appear generally consistent with those found in the central regions of nearby starburst galaxies. On the other hand, if the molecular emission is dominated by a gravitationally lensed core only $\sim 100\ h^{-1}$ pc in size, then the physical conditions of this gas appear to be less extreme than those found at a similar size scale in NGC 1068, which harbors an active nucleus.

To discriminate among the alternatives will require subarcsecond observations that resolve the source structure. Using the longer baselines and/or the higher frequencies now available to the expanded millimeter arrays, sufficiently high resolution may be obtained. With a resolved image, it will be possible to determine unambiguously the location of the molecular emission with respect to the optical emission, to construct improved lens models, and to estimate with confidence the location and physical extent of the molecular gas.

4.2. *Simultaneous Observations of High-z Molecular Lines*

While the sensitivity obtained in the present study of H1413+117 is limited, it demonstrates that the simultaneous observation of multiple molecular lines is a technique that need not be restricted to Galactic objects. For the present generation of millimeter interferometers, with typical IF bandwidths of 1 GHz and local oscillators providing sideband separations of ~3 GHz, pairs of interesting (and perhaps detectable) lines are accessible over a remarkable range of redshift. Considering only lines of the species HCO^+ (to $J = 10$), HCN (to $J = 10$), and CS (to $J = 20$), the redshift range $0 < z < 6$, and line pair separations 0–6 GHz, Figure 3 shows graphically the high-density tracer lines that may be observed simultaneously with a CO line (to $J = 10$) in the frequency range 80–115 GHz. For H1413+117, at $z = 2.56$, the CO (3–2) and HCO^+ (4–3) lines are separated by 3.07 GHz. In Figure 3, this line pair is represented by the arc located near the center. The ends of the arc correspond to frequencies where the redshift moves one of the lines out of the 80–115 GHz band. This analysis is easily extended to more species and frequency bands to locate additional useful line pairs. For example, the CO (7–6) and HCN (9–8) lines from H1413+117, redshifted to 1.3 mm, are separated by 2.6 GHz and are therefore accessible to simultaneous observation.

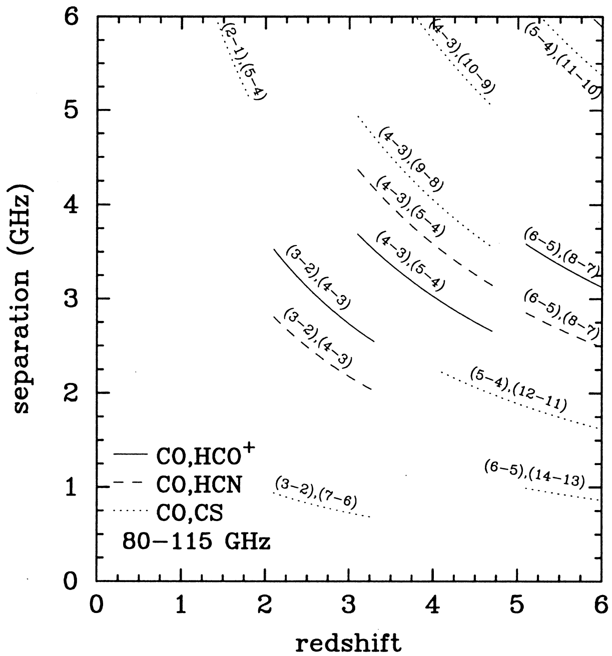

FIG. 3.—Lines of the species HCO^+ (to $J = 10$–9), HCN (to $J = 10$–9), and CS (to $J = 20$–19), that may be observed together with a CO line (to $J = 10$–9) in the frequency range 80–115 GHz, for redshift $0 < z < 6$ and line pair separations from 0–6 GHz (see § 4.2.).

Future interferometric observations of molecular line pairs, or perhaps two or more molecular line pairs using multiple receivers, may prove most useful for compact, high-density regions that are highly magnified by gravitational lensing.

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