THE ASTROPHYSICAL JOURNAL, 477:L33–L36, 1997 March 1


# ATOMIC CARBON IN M82: PHYSICAL CONDITIONS DERIVED FROM SIMULTANEOUS OBSERVATIONS OF THE [C I] FINE-STRUCTURE SUBMILLIMETER-WAVE TRANSITIONS

J. STUTZKI, U. U. GRAF, S. HAAS, C. E. HONINGH, D. HOTTGENROTH, K. JACOBS, R. SCHIEDER, R. SIMON, J. STAGUHN, AND G. WINNEWISSER
I. Physikalisches Institut der Universität zu Köln, Zülpicher Straße 77, D-50937 Köln, Germany

AND

R. N. MARTIN, W. L. PETERS, AND J. P. MCMULLIN
Steward Observatory, University of Arizona, Tucson, AZ 85721
*Received 1996 October 9; accepted 1996 December 21*

## ABSTRACT

We report the first extragalactic detection of the neutral carbon [C I] $^3P_2 \rightarrow {^3P_1}$ fine-structure line at 809 GHz. The line was observed toward M82 simultaneously with the $^3P_1 \rightarrow {^3P_0}$ line at 492 GHz, providing a precise measurement of the $J = 2 \rightarrow 1/J = 1 \rightarrow 0$ integrated line ratio of 0.96 (on a [K km s$^{-1}$] scale). This ratio constrains the [C I] emitting gas to have a temperature of at least 50 K and a density of at least $10^4$ cm$^{-3}$. Already at this minimum temperature and density, the beam averaged C I column density is large, $2.1 \times 10^{18}$ cm$^{-2}$, confirming the high C I/CO abundance ratio of $\approx$0.5 estimated earlier from the 492 GHz line alone. We argue that the [C I] emission from M82 most likely arises in clouds of linear size around a few pc with a density of about $10^4$ cm$^{-3}$ or slightly higher and temperatures of from 50 K up to about 100 K.

*Subject headings:* galaxies: individual (M82) — galaxies: ISM — galaxies: starburst — ISM: abundances — radio lines: ISM

## 1. INTRODUCTION

The fine-structure lines of neutral atomic carbon, [C I], $^3P_2 \rightarrow {^3P_1}$ at 809.3435 GHz and $^3P_1 \rightarrow {^3P_0}$ at 492.1607 GHz (Cooksy et al. 1986; Yamamoto & Saito 1991) provide an important diagnostic tool for the physical and chemical conditions of the dense interstellar medium and contribute significantly to the energy balance of the gas. After the first detections ($^3P_1 \rightarrow {^3P_0}$, Phillips et al. 1980; $^3P_2 \rightarrow {^3P_1}$, Jaffe et al. 1985) the rapid advance in receiver sensitivity, driven by the technological progress of superconducting mixers now reaching sensitivities of only a few times the quantum limit even at submillimeter wavelengths, has resulted in the $J = 1 \rightarrow 0$ line now being well studied in many galactic sources.

The three detections of the [C I] $^3P_1 \rightarrow {^3P_0}$ line in external galaxies (IC 342, Büttgenbach et al. 1992; M82, Schilke et al. 1993 and White et al. 1994; NGC 253, Harrison et al. 1995) show that C I exhibits rather different properties in these starburst galaxies from the ones in the Milky Way as measured by *COBE* (Wright et al. 1991; Bennett et al. 1994). Both in M82 and in NGC 253 the C I/CO abundance ratio is rather high, 0.4–0.5, whereas it is only about 0.1 even in massive star-forming regions in the Milky Way. Observations of the upper, $^3P_2 \rightarrow {^3P_1}$, transition are still rather rare, since only few receiver systems are operational at these wavelengths.

The [C I] fine-structure line intensity ratio is of particular astrophysical importance. In the optically thin regime the integrated line intensity is proportional to the upper state column density. The line intensity ratio thus directly measures the $J = 2 \rightarrow 1$ excitation temperature, $(g_2/g_1) \exp(-h\nu_{21}/kT_{ex}) = N_2/N_1$. Measuring the integrated line intensity on a [K km s$^{-1}$] scale, $R = \int T_{mb,\,2\rightarrow 1}\, dv / \int T_{mb,\,1\rightarrow 0}\, dv$, and using the values for the *A*-coefficients given by Nussbaumer & Rusca (1979), we obtain $T_{ex} = 38.8\ \mathrm{K}/\ln[2.11/R]$. More generally, an escape probability radiative transfer model, covering also the case of higher optical depth, links the observed line ratio with the physical parameters of the source.

In this Letter we report the first extragalactic detection of the [C I] $^3P_2 \rightarrow {^3P_1}$ line, which was observed from the starburst galaxy M82 simultaneously with the $^3P_1 \rightarrow {^3P_0}$ line, thus providing a very good relative calibration of the line ratio and hence allowing an accurate estimate of the excitation conditions in the [C I] emitting gas.

## 2. OBSERVATIONS

The two neutral atomic carbon fine-structure lines were observed simultaneously using a new dual-channel receiver built at the Universität zu Köln (Honingh et al. 1997). Both channels have a tunerless SIS waveguide mixer furnished with SIS junctions designed and fabricated in the Cologne microstructure laboratory. One operates from 780 to 820 GHz in DSB mode with $T_{rec} = 1100$ K; the other, from 460 to 490 GHz, is SSB tuned with a Martin-Puplett interferometer. Due to technical problems with a cooled IF-amplifier, the low-frequency channel had a $T_{rec(SSB)}$ of only 700 K, rather poor in comparison with its standard performance ($T_{rec(SSB)} = 160$ K) but still better than the high-frequency channel and thus not limiting the sensitivity for the simultaneous measurement. These observations, performed on 1996 March 3 are the first heterodyne measurements at frequencies above 460 GHz with the new 10 m Heinrich Hertz Telescope (Baars et al. 1997) on Mount Graham, Arizona.

The receiver package includes a dual-channel acousto-optical spectrometer back end with a 1.1 GHz bandwidth each and 1 MHz resolution (Schieder, Tolls, & Winnewisser 1989). Calibration is done via an internal hot load/cold load/sky-flip mirror, following the procedure outlined in Harris (1986) and including corrections for atmospheric sideband imbalance derived from standard atmospheric models (Grossman 1989).

The zenith transmission was 0.41 at 809 GHz and 0.54 at 492 GHz for an 8 hr period during which the M82 data were taken. Note that the ratio of transmissions predicted by the standard atmospheric model is 0.96. The difference is likely caused by a vertical structure of the atmosphere different from the model assumptions.

Line intensities are given in units of $T_{mb} = T_A/(\eta_{mb}e^{-\tau})$. Main beam efficiencies were determined according to $\eta_{mb} = T_{A,P}/(\eta_c T_P e^{-\tau})$, where $T_{A,P}$ is the antenna temperature measured on a planet, $T_P$ the Rayleigh-Jeans temperature of the planet disk, and $\eta_c = 1 - \exp[-\ln 2(d_P/\theta_{FWHM})^2]$ the geometric coupling factor between the planet (disk diameter $d_P$) and the Gaussian beam. $\eta_{mb} = 0.16$ was derived for the 9″ FWHM 809 GHz beam, and $\eta_{mb} = 0.29$ for the 15″ FWHM 492 GHz beam from measurements of Venus (17″ diameter), assuming its physical temperature to be 280 K (Altenhoff 1985). Subsequent realignment of the secondary mirror improved these efficiencies, but it is irrelevant for the data presented here. Due to the simultaneous observation of both lines, the line intensity ratio is measured very precisely. Combining the above relations, the line ratio is effectively calibrated against the observed intensity ratio of the planet and is given by

$$\frac{T_{mb,1}}{T_{mb,2}} = \frac{T_{A,1}}{T_{A,2}}\left(\frac{T_{A,P,2}}{T_{A,P,1}}\frac{\eta_{c,1}T_{P,1}}{\eta_{c,2}T_{P,2}}\right)\exp[-(\Delta\tau_L - \Delta\tau_P)],$$

where $\Delta\tau = \tau_1 - \tau_2$ is the difference of the atmospheric opacity at both line frequencies. Indices L and P distinguish the *line* and *planetary* measurements. As the atmospheric transmission at the [C I] fine-structure transition frequencies is of comparable magnitude, and as long as the planetary calibration measurement and the source observations are done at roughly the same transmission, the $\exp[-(\Delta\tau_L - \Delta\tau_P)]$ factor is always close to unity and depends only weakly on the actual transmission. The error in the line ratio is thus dominated by the uncertainty in the coupling factor, i.e., the uncertainty of the beam sizes at the two frequencies. We did not have a smaller planet than Venus available for calibration at the period of the observations, and were thus not able to measure the beam sizes directly with sufficient precision. Instead, we use the nominal sizes quoted above, corresponding to the diffraction limit of a Cassegrain optics with 14 dB edge taper (Goldsmith 1982).

The observations were done using the secondary chopping mirror with a 2′ throw at 2 Hz in azimuth and alternatingly pointing the telescope with the source in one and the other chopper beam. As the observations were done in one of the first nights after the receiver was installed, we did not yet have a good pointing model available. We nevertheless found emission from the SW lobe of M82, clearly identifiable via its line shape and velocity. We mapped several positions on a 5″ grid around the position of strongest emission. Unfortunately, we were not able to extend our observations to the center and the NE lobe of M82 due to technical problems with the telescope drive software after about 2 hr of observing. Pointing observations over the subsequent days confirmed the M82 observations to be pointed on the SW lobe of the galaxy.

## 3. RESULTS AND DISCUSSION

Figures 1*a* and 1*b* shows the positionally averaged spectra obtained by summing 33 scans of 2 minutes duration each, pointed at eight positions within a 7″ radius from the position of maximum signal. It thus represents the emission in a beam of effectively 14″ FWHM for the 809 GHz and 20″ for the 492 GHz line. Both [C I] lines are clearly detected with their line shape consistent with the earlier observations of the [C I] 492 GHz emission from the SW lobe by Schilke et al. (1993). The intensity of the 492 GHz line agrees with that reported in the same beam size by those authors. No baseline correction has been applied to the spectra displayed in Figures 1*a* and 1*b*. The observed continuum offsets (0.6 K [DSB] at 809 GHz, i.e., 23 Jy in the effective 14″ beam; 0.15 K [SSB] at 492 GHz, i.e., 8 Jy in the effective 20″ beam) are within the errors consistent with the broadband dust continuum fluxes (450 $\mu$m, Smith et al. 1990; 800 $\mu$m, Hughes, Gear, & Robson 1990; 1300 $\mu$m, Krügel et al. 1990).

At 809 GHz the intensity at the map center is significantly higher than the map average (Fig. 1*a*). The $J = 2 \rightarrow 1$ line emission is thus more compact than the map extent. The 492 GHz line does not show as big an effect (Fig. 1*b*),

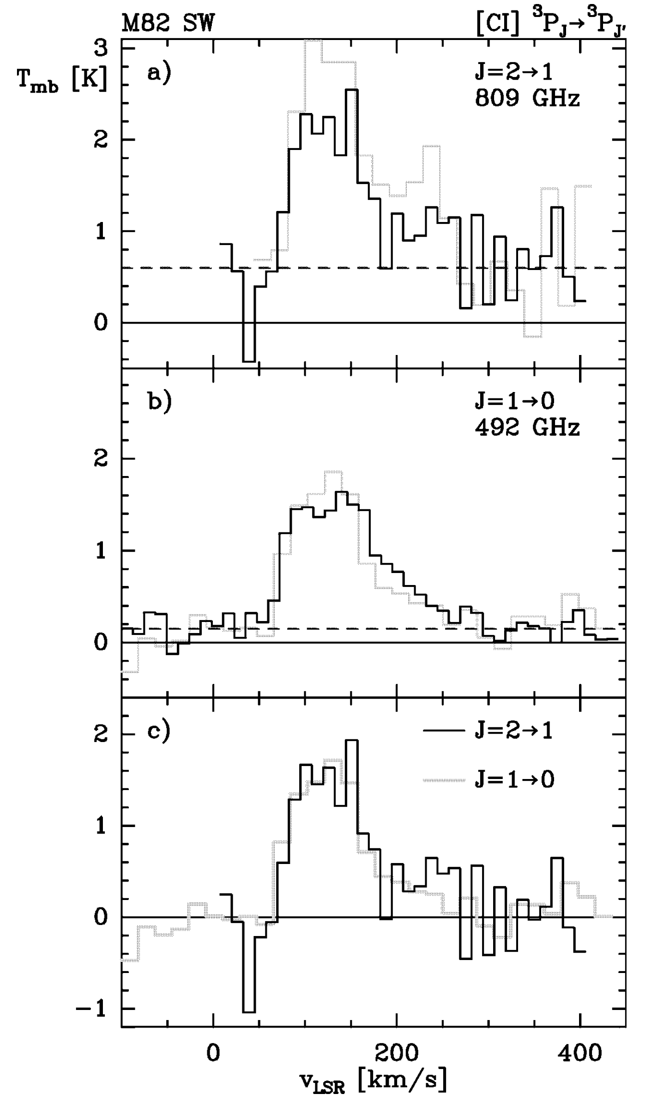


FIG. 1.—[C I] spectra of M82: (*a*) *black*, [C I] $^3P_2 \rightarrow {}^3P_1$ emission averaged over an effectively 14″ diameter area. *Gray*, spectrum at the peak of the map. The continuum offset (*dashed line*) corresponds to the known dust emission. (*b*) Same, but for the [C I] $^3P_1 \rightarrow {}^3P_0$ line. (*c*) overlay of the continuum subtracted [C I] $^3P_2 \rightarrow {}^3P_1$ map average and $^3P_1 \rightarrow {}^3P_0$ peak spectrum.

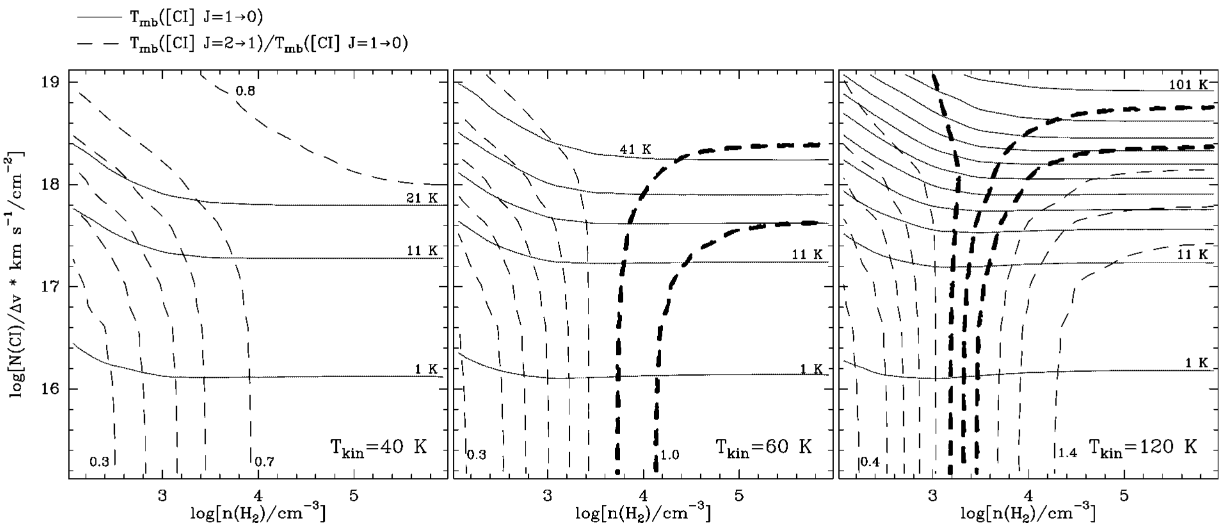


FIG. 2.—Escape probability radiative transfer analysis of the [C I] emission: $J = 1 \rightarrow 0$ line brightness temperature (*solid contours, increasing bottom to top*) and the brightness ratio between the $J = 2 \rightarrow 1$ and $J = 1 \rightarrow 0$ line (*dashed contours, increasing left to right*) are plotted in a density/column density plane at three different kinetic temperatures. For comparison with the observed line ratio the ratio contours at 0.9, 1.0, and 1.1 are drawn as heavy dashed lines. In the optically thin regime, a 1 K bright $^3P_1 \rightarrow {}^3P_0$ line corresponds to a beam averaged C I column density of $1.3 \times 10^{16}$ cm$^{-2}$ per 1 km s$^{-1}$ velocity interval.

consistent with it being observed with the larger beam of 15″ FWHM anyway. For the analysis of the line ratio we thus compare the 809 GHz map average with the 492 GHz center spectrum (Fig. 1*c*). The integrated intensity is 152 K km s$^{-1}$ for the $J = 2 \rightarrow 1$ and 158 K km s$^{-1}$ for the $J = 1 \rightarrow 0$ line, $R =$ 0.96, which, as discussed above, should be accurate to within 10%. The [C I] intensity ratio in M82 is thus much higher than in the Milky Way: the large-scale *COBE* maps (Bennett et al. 1994) give $R = 0.35$ for the Galactic Center emission, and $R =$ 0.17 for the inner Galactic disk. Following the derivation in the introduction, the excitation temperature of the $J = 2 \rightarrow 1$ transition, and hence, the minimum kinetic temperature of the [C I] emitting gas in M82, is $T_{ex} = 50$ K. The corresponding value from *COBE* for the Galactic Center is $T_{ex} = 22$ K, for the inner Galactic disk it is $T_{ex} = 15$ K.

Figure 2 shows the result of an escape probability radiative transfer calculation (Stutzki & Winnewisser 1985) for spherical clumps, using the $H_2$ collisional rate coefficients by Schröder et al. (1991). It confirms the minimum temperature of 50 K. At this temperature the line ratio implies a gas density of at least $10^4$ cm$^{-3}$. At higher temperatures a lower density is possible ($2 \times 10^3$ cm$^{-3}$ at $T_{kin} = 120$ K). Densities higher than the quoted minimum require the line to be optically thick and thermalized, and hence, they can only be reached at very high C I column densities (on the horizontal branch of the according contour lines in Fig. 2). The minimum kinetic temperature and density derived are in good agreement with the estimates for the excitation conditions of the bulk CO emission from M82 (Turner, Martin, & Ho 1990; Harris et al. 1991; Wild et al. 1992; Güsten et al. 1993). The [C I] line ratio constrains the pressure of the interstellar medium in M82 to be $5 \times 10^5$ K cm$^{-3}$ or higher.

The absolute line intensities correspond to a beam averaged C I column density of $2.1 \times 10^{18}$ cm$^{-2}$. This value depends only weakly on the temperature and density of the gas (see Fig. 2). This is plausible, as the partition function of the three-level system C I does not change significantly above a $T_{ex}$ of about 20 K, as was noted already by Schilke et al. (1993). Comparison with the total CO column density of $4 \times 10^{18}$ cm$^{-2}$ derived by Wild et al. (1992) both from the $C^{18}O$ low $J$ intensities and an excitation model for all observed CO lines, then gives a high C I/CO abundance ratio of 0.5, confirming the high value found by Schilke et al. (1993) and White et al. (1994).

The reason for the high C I/CO ratio in M82 in comparison to typical Galactic sources with a similar UV field intensity and comparable densities, is unclear. It might primarily be a geometrical effect, where a much smaller fraction of the presumably highly clumped material is located at sufficient column density to be well shielded from the UV radiation than is the case for typical Galactic sources; the cause for this would, of course, be linked to the rather different physical environment created by the starburst activity in M82. Schilke et al. (1993) argue that at the enhanced cosmic-ray flux in M82 (Suchkov, Allen, & Heckman 1993), resulting from the high SN rate (Kronberg, Biermann, & Schwab 1985) following the starburst, the high-ionization solution found by Le Bourlot et al. (1992) for low-density material in dark interstellar clouds with its correspondingly large C I/CO ratio will be a stable solution of the chemical network even at the high densities of the interstellar medium in M82. The high cosmic-ray flux also explains the high temperature of the ambient molecular cloud material. Störzer, Stutzki, & Sternberg (1997) point out that the C II layer in a PDR rapidly recombines, but only slowly forms CO, leading to a layer with enhanced C I abundance for about $10^5$ yr when the illuminating UV radiation is switched off. Under repeated exposure to UV, as will naturally occur in a turbulent, clumpy medium where the clumps mutually shadow each other, this will on time average lead to a significantly enhanced C I emission, in particular if the medium stays warm, as will be the case in clouds like the Galactic Center clouds or the interstellar medium in M82. Which of these proposed mechanisms (and possibly others) provide the right explanation for the enhanced C I abundance in M82 and other starburst galaxies has to await further investigation.

The measured line ratio allows the determination of an upper limit to the C I column density as long as the [C I] emitting gas has temperatures below about 100 K. Higher temperatures, however, are rather unlikely as there is no known mechanism that would heat the bulk of the gas to such high temperatures and yet keep the dust cool enough to be consistent with the observed dust continuum emission. At temperatures of about 50 K the observed line ratio implies an upper limit to the C I column density of about $4 \times 10^{19}$ $cm^{-2}$ (with the equivalent width of the line of 100 km $s^{-1}$), 20 times larger than the beam averaged column density. The filling factor of individual clumps hence must be about 5% or larger. At these high column densities both [C I] lines become close to optically thick.

We now argue, that the [C I] emitting gas in M82 originates most likely from a large number of small clumps, where the individual clumps reach column densities close to the upper limit discussed above. With (1) a C I/CO abundance ratio of 0.5, (2) a total gas phase abundance of C/H of $10^{-4}$, (3) assuming the gas phase carbon abundance to be dominated by CO and C I, and (4) an $H_2$ volume density of about $10^4$ $cm^{-2}$ estimated from the excitation analysis, a C I column density of $2.1 \times 10^{18}$ $cm^{-2}$ corresponds to a geometric depth of the cloud of only 0.5 pc, or 0″.03 at the distance of M82 of 3.25 Mpc (Tamman & Sandage 1968). Even at the upper range of column densities derived above, i.e., $1.5 \times 10^{19}$ $cm^{-2}$ for a giant molecular cloud complex with a 30 km $s^{-1}$ wide line, the linear scale reaches only 3.6 pc, or about 0″.22. This angular scale is consistent with the beam filling factor estimated above, assuming the emission to arise from on the order of 100 such complexes within the beam. In fact, structure is visible down to at least 2″ on interferometric maps both in CO $J = 2 \rightarrow 1$ (Shen & Lo 1995) and in the high-density tracing molecule HCN (Brouillet & Schilke 1993). Higher densities would imply smaller clump sizes and hence a larger number of clumps in the beam. At higher temperatures the upper limit to the column density becomes higher (by an order of magnitude at 120 K), and accordingly larger clump sizes are possible. The most likely scenario explaining the observed [C I] line emission is thus an ensemble of cloud complexes with linear sizes of a few pc and densities of several $10^4$ $cm^{-3}$, their temperatures ranging between about 50 K and up to about 100 K.

In summary, our simultaneous observations of both [C I] fine-structure lines at 809 and 492 GHz constrain the physical conditions in the [C I] emitting gas to densities of $10^4$ $cm^{-3}$ or slightly higher and temperatures of 50 K, possibly up to 100 K for a fraction of the gas. The analysis confirms the high C I/CO abundance ratio of 0.5 in the starburst galaxy M82. The emission arises in many cloud complexes of a few pc extent, which individually reach optical depths close to unity in the [C I] lines.

This research was supported by the Verbundforschung Astronomie through grant 05 2KU134(6) and by the Deutsche Forschungsgemeinschaft through grant SFB 301. Special thanks go to members of the SMT technical staff for their help during setup of the instrument and interfacing it to the telescope.

## REFERENCES

Altenhoff, W. 1985, in Proc. ESO-IRAM-Onsala Workshop on Submillimeter Astronomy, ed. P. A. Shaver, K. Kjaer (Garching: ESO), 591
Baars, J. W. M., Martin, R. N., Mangum, J., McMullin, J., Peters, W. 1997, in preparation
Bennett, C. L., et al. 1994, ApJ, 434, 587
Brouillet, N., & Schilke, P. 1993, A&A, 277, 381
Büttgenbach, T. H., Keene, J., Phillips, T. G., & Walker, C. K. 1992, ApJ, 397, L15
Cooksy, A. L., Saykally, R. J., Brown, J. M., & Evenson, K. M. 1986, ApJ, 309, 828
Goldsmith, P. F. 1982, in Infrared and Millimeter Waves, Vol. 6: Systems and Components, ed. K. J. Button (New York: Academic Press), 277
Grossman, E. 1989, AT-Atmospheric Transmission Software, User Manual (Austin: Univ. Texas)
Güsten, R., Serabyn, E., Kasemann, C., Schinkel, A., Schneider, G., Schulz, A., & Young, K. 1993, ApJ, 402, 537
Harris, A. I. 1986, Ph.D. thesis, Univ. California, Berkeley
Harris, A. I., Hills, R. E., Stutzki, J., Graf, U. U., Russell, A. P. G., & Genzel, R. 1991, ApJ, 382, L75
Harrison, A., Puxley, P., Russel, A., Brand, P. 1995, MNRAS, 277, 413
Honingh, C. E., Hottgenroth, D., Haas, S., Jacobs, K., Graf, U. U., & Stutzki, J. 1997, Int. J. Infrared Millimeter Waves, submitted
Hughes, D. H., Gear, W. K., & Robson, E. I. 1990, MNRAS, 244, 759
Jaffe, D. T., Harris, A. I., Silber, M., Genzel, R., & Betz, A. L. 1985, ApJ, 290, L59
Kronberg, P. P., Biermann, P., & Schwab, F. R. 1985, ApJ, 291, 693
Krügel, E., Chini, R., Klein, U., Lemke, R., Wielebinski, R., & Zylka, R. 1990, A&A, 240, 232
Le Bourlot, J., Pineau des Forêts, G., Roueff, E., Flower, D. R. 1992, A&A, 267, 233
Nussbaumer, H., & Rusca, C. 1979, A&A, 72, 129
Phillips, T. G., Huggins, P. J., Kuiper, T. B. H., & Miller, R. E. 1980, ApJ238, L103
Schieder, R., Tolls, V., & Winnewisser, G. 1989, Exp. Astron., 1, 101
Schilke, P., Carlstrom, J. E., Keene, J., & Phillips, T. G. 1993, ApJ, 417, L67
Schröder, K., Staemmler, V., Smith, M. D., Flower, D. R., & Jaquet, R. 1991, J. Phys. B, 24, 2487
Shen, J., & Lo, K. Y. L. 1995, ApJ, 445, L99
Smith, P. A., Brand, P. W. J. L., Puxley, P. J., Mountain, C. M., & Nakai, N. 1990, MNRAS, 243, 97
Störzer, H., Stutzki, J., & Sternberg, A. 1997, ApJ, submitted
Stutzki, J., & Winnewisser, G. 1985, A&A, 144, 13
Suchkov, A., Allen, R. J., & Heckman, T. M. 1993, ApJ, 413, 542
Tammann, G. A., & Sandage, A. 1968, ApJ, 151, 825
Turner, J. L., Martin, R. N., & Ho, P. T. P. 1990, ApJ, 351, 418
White, G. J., Ellison, B., Claude, S., Dent, W. R. F, & Matheson, D. N. 1994, A&A, 284, L23
Wild, W., Harris, A. I., Eckart, A., Genzel, R., Graf, U. U., Jackson, J. M., Russell, A. P. G. R., & Stutzki, J. 1992, A&A, 25, 447
Wright, E. L., et al. 1991, ApJ, 381, 200
Yamamoto, S., & Saito, S. 1991, ApJ, 370, L103