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MOLECULAR ABSORPTION LINES TOWARD THE NUCLEUS OF CENTAURUS A

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ABSTRACT

We present measurements of absorption lines of ^{12}CO, ^{13}CO, HCO^+, HCN, CN, and CS toward the nuclear continuum source of Centaurus A obtained with the Swedish-ESO Submillimeter Telescope (SEST). The spectra show a number of features with line widths of a few km s^{-1}. They can be attributed to individual molecular clouds with properties similar to dense molecular clouds in our Galaxy. CO absorption-line ratios, as well as the hyperfine line ratios for CN and HCN, indicate that the deepest absorption at the systemic velocity of Centaurus A originates in quiescent molecular clouds that are cold, dense, and clumped and happen to lie along the line of sight to the central compact continuum source. Combining CO, H I, and 9.7 μm silicate absorption data, we obtain a ^{12}CO fractional abundance of (5–11) $\times 10^{-5}$ which is in excellent agreement with the typical values derived for the dense interstellar medium in our Galaxy (8×10^{-5}). Fractional abundances also of the other observed molecular species are comparable to those found in Galactic molecular clouds and in other galaxies.

For the central absorption feature the ^{12}CO and ^{13}CO $J = 2$–1 to $J = 1$–0 line ratio, as well as a limit on this ratio for CN, indicate that the absorption occurs in very cold and/or subthermally excited gas. For this absorbing component LTE and non–LTE model calculations indicate a kinetic temperature between 4 K and 10 K, ^{12}CO column densities of about (3–5) $\times 10^{17}$ cm^{-2}, and hydrogen volume densities near the critical density of 2×10^4 cm^3 required to populate the $J = 2$ level. The physical properties of the absorbing gas are comparable to those of the emitting molecular gas in the disk of Centaurus A.

The fact that the absorbing molecular gas is cold and dense is in agreement with the finding that at the mean distance of the absorbing gas of 1 kpc radiative excitation from the nuclear source is not important. For the weak, broad, redshifted absorption features, neither a close proximity to the nucleus nor the importance of the nuclear continuum radiation field for their molecular excitation can be excluded.

Subject headings: galaxies: individual (NGC 5128) — galaxies: interstellar matter — interstellar: molecules

I. INTRODUCTION

The combination of a dust lane straddling an elliptical light distribution, extensive radio lobes and jets, a strong nuclear continuum source and, perhaps most crucially, its proximity (about 3 Mpc; de Vaoucouleurs 1979) have made Centaurus A (NGC 5128) one of the most frequently observed radio galaxies. It is now becoming clear that its peculiar morphology is probably a mere consequence of its proximity (Ebneter and Balick 1983).

The study of the molecular interstellar medium in Centaurus A has begun only recently with the advent of large millimeter telescopes capable of accessing a declination of −43°. In a previous paper (Eckart *et al.* 1990*a*, hereafter Paper I) we presented a fully sampled map of the $^{12}CO(1$–$0)$ distribution in the disk which complements the $^{12}CO(2$–$1)$ cuts obtained by Phillips *et al.* (1987) and Phillips, Sanders, and Sargent (1989). From these data we determined that the ISM in the disk of Centaurus A is cold ($T < 10$ K), with densities of the order of the ^{12}CO critical density ($\sim 2 \times 10^4$ cm^{-3}), required to populate the $J = 2$ level.

Absorption against the nuclear continuum source has been reported for H I (van Gorkom 1987; van der Hulst, Golisch, and Haschick 1983; Whiteoak and Gardner 1971) and a number of molecular species, such as OH, H_2CO, C_3H_2, ^{12}CO, and ^{13}CO (Whiteoak and Gardner 1971; Gardner and Whiteoak 1976; Bell and Seaquist 1988; Phillips *et al.* 1987; Israel *et al.* 1990). Here we present measurements of absorption in the lines of ^{12}CO, ^{13}CO, HCO^+, HCN, CN, and CS. Our analysis shows that the lines are due to absorption of the nonthermal continuum of the milliarcsecond nucleus of Centaurus A, rather than due to self-absorption of molecular clouds. Therefore, the absorption lines provide a "pencil beam" measurement of the characteristics of the molecular clouds responsible for the absorption features and give a deeper insight into the properties of the molecular interstellar medium in this peculiar galaxy.

II. OBSERVATIONS

The observations were carried out using the Swedish-ESO Submillimeter Telescope (SEST) in La Silla, Chile, during 1989 July and December. The beamwidths (FWHM) are 45″ and 22″ at 115 GHz and 230 GHz, respectively. At both frequencies, we used dual-polarized, cooled Schottky mixers with receiver temperatures of about 350 and 650 K (both SSB), respectively. The system was calibrated using the chopper wheel method (Ulich and Haas 1976) and by observations of Saturn. The pointing was checked by monitoring the central line profile and continuum level of Centaurus A itself. A focal plane chopper switched between two beams symmetrically displaced in azimuth on each side of the telescope axis with a beam separation of

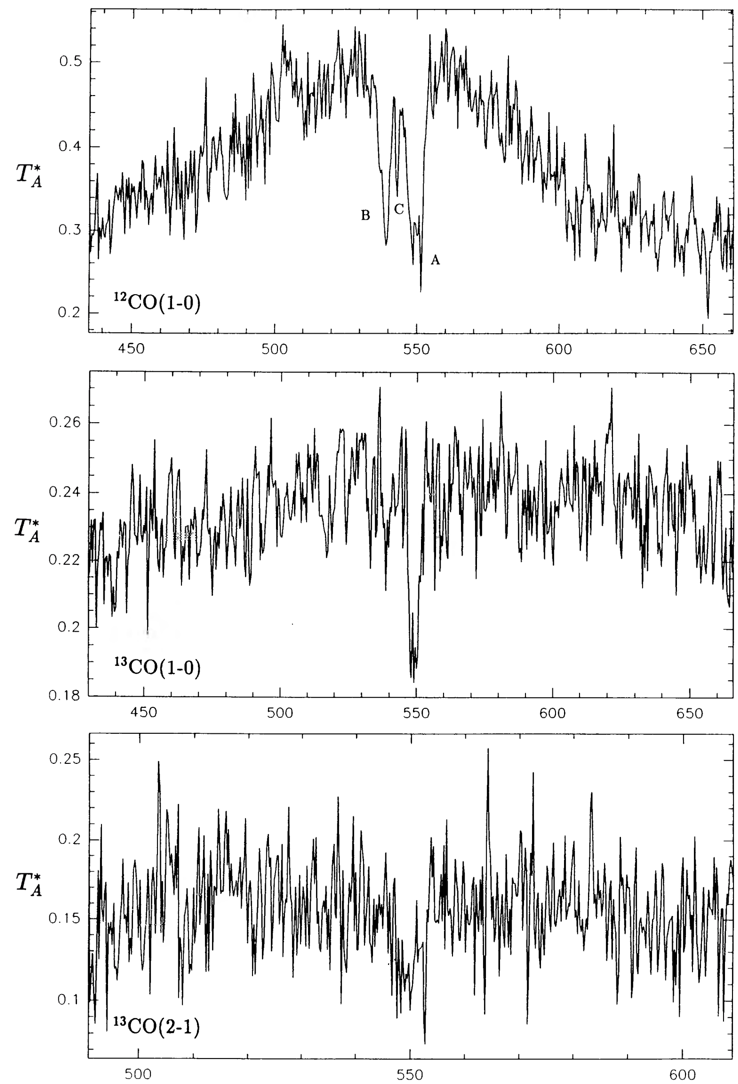

FIG. 1.—Absorption lines observed toward the nucleus of Centaurus A. In the $^{12}CO(1\text{–}0)$ and $HCO^+(1\text{–}0)$ spectra, we indicated the individual absorption features A to E. In the HCN and CN spectra, we included the hyperfine line designations and marked their expected velocities with arrows. The spectral resolutions are 0.45, 0.48, 0.24, 0.59, 0.26, 0.36, and 0.47 km s^{-1} for the $^{12}CO(1\text{–}0)$, $^{13}CO(1\text{–}0)$, $^{13}CO(2\text{–}1)$, $HCO^+(1\text{–}0)$, CS(2–1), HCN(1–0), and CN(1–0) spectra, respectively.

approximately 12′ on the sky. As backend we used a narrow-band AOS offering a maximum resolution of 50 kHz in a 100 MHz bandwidth (Booth *et al.* 1989).

The total integration time per spectrum ranged between 1 and 8 hr depending on the observing frequency and the molecular species. Figure 1 shows a summary of molecular absorption features we observed toward the nucleus of Centaurus A. A map of the $^{12}CO(1\text{–}0)$ absorption shows that it is centered on the nonthermal continuum source and is spatially unresolved. Table 1 lists the integration times, center velocities, peak intensities, and widths of the absorption lines as well as the continuum level and the derived optical depths. The $^{12}CO(2\text{–}1)$ values were estimated from Figure 3 in Phillips, Sanders, and Sargent (1989).

a) Line Features

The spectra in Figure 1 show a number of different absorption features. They are most easily discussed using the $HCO^+(1\text{–}0)$ spectrum. This spectrum is free of hyperfine structure line splitting and "contaminating" line emission, and all the features that can be identified in other spectra are present. Most prominent are three narrow features. The strongest feature, A, is at the systemic velocity of $v_{LSR} = 550 \pm 1$ km s^{-1} and the next strongest feature, B, is at a velocity of 540 ± 1 km s^{-1}. The very narrow feature, C, at 544 ± 1 km s^{-1} is also present in the $^{12}CO(1\text{–}0)$ spectrum and in $HCO^+(1\text{–}0)$ and $^{12}CO(1\text{–}0)$ spectra taken independently (Israel *et al.* 1990; F. P. Israel, private communication). The $HCO^+(1\text{–}0)$ spectrum reveals a broad complex of weak redshifted absorption-line features. There are two troughs centered at about 580 km s^{-1} and 604 km s^{-1}. This redshifted absorption is also visible in the CN(1–0) and probably indicated in the $^{13}CO(1\text{–}0)$ spectrum. The velocity and large line widths of these two broad redshifted features suggest that they correspond to the H I absorptions at 576 and 595.5 km s^{-1} which have been attributed to infalling gas within 500 pc of the nucleus (van der

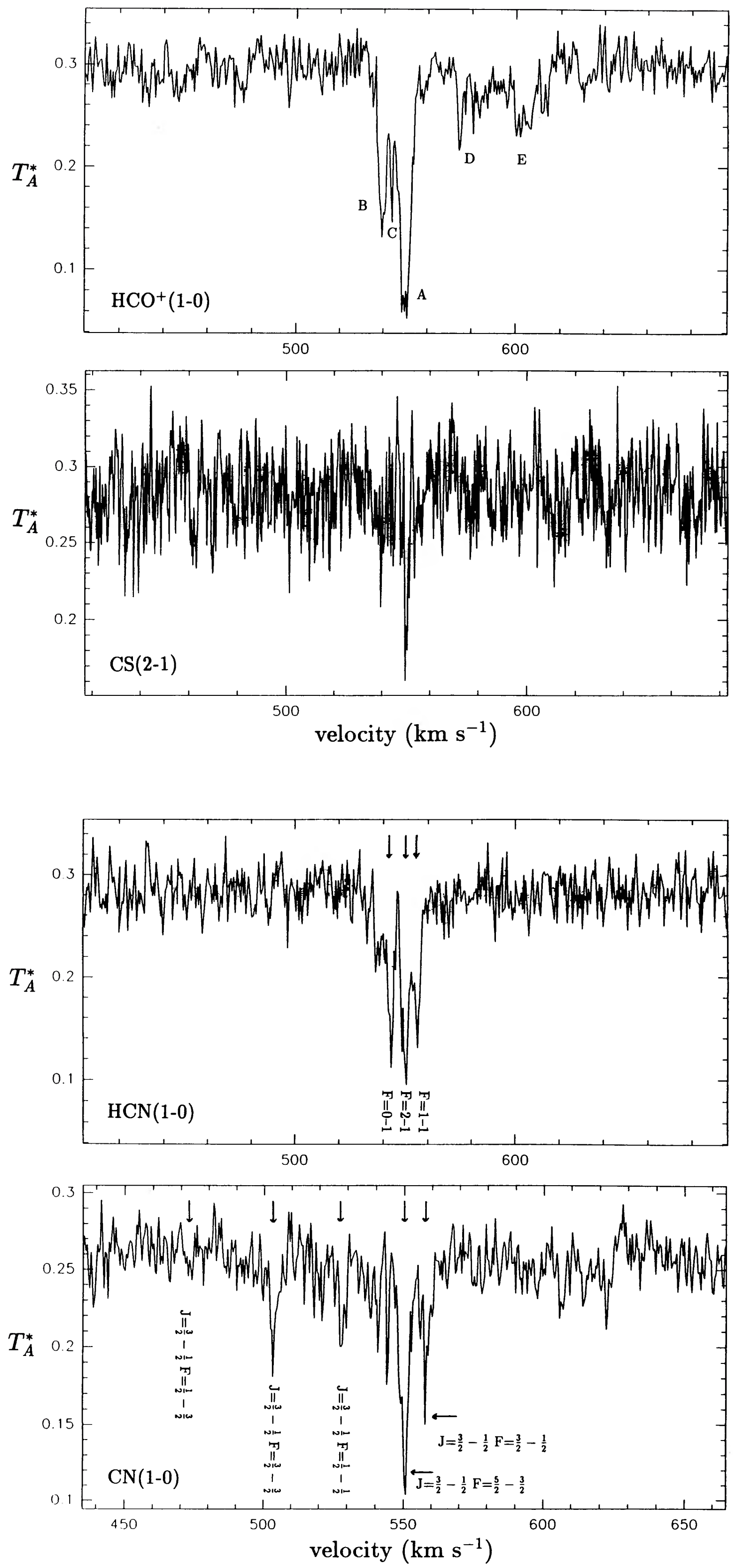

FIG. 1—*Continued*

TABLE 1

MOLECULAR ABSORPTION-LINE DATA

Molecule	Transition	t_{int} (minutes)	v_{center} [a] (km s^{-1})	T_c^* [b]	T_{peak}^* [b]	Δv_{FWHM} (km s^{-1})	τ_{peak}
HCN	$J = 1–0, F = 1–1$	112			0.16		
	$J = 1–0, F = 2–1$		550	0.28	0.19	5	1.1
	$J = 1–0, F = 0–1$				0.17		
HCO^+	$J = 1–0$	190	A 550	0.29	0.23	7	1.6
			B 544		0.17	<3	0.9
			C 540		0.15	5	0.7
			D 580		0.08	~14	0.3
			E 604		0.07	~14	0.3
CS	$J = 2–1$	490	550	0.28	0.14	<2	0.7
CN	$N = 1–0, J = \frac{3}{2}–\frac{1}{2}, F = \frac{3}{2}–\frac{1}{2}$				0.10		
	$N = 1–0, J = \frac{3}{2}–\frac{1}{2}, F = \frac{5}{2}–\frac{3}{2}$	200	550	0.24	0.15	4	1.0
	$N = 1–0, J = \frac{3}{2}–\frac{1}{2}, F = \frac{1}{2}–\frac{1}{2}$				0.06		
	$N = 1–0, J = \frac{3}{2}–\frac{1}{2}, F = \frac{3}{2}–\frac{3}{2}$				0.07		
	$N = 1–0, J = \frac{3}{2}–\frac{1}{2}, F = \frac{1}{2}–\frac{3}{2}$				<0.02		
	$N = 2–1$	100	...		<0.05		
^{12}CO	$J = 1–0$	76	550	0.22	>0.20	6	>2.4
			544		0.16	<2	
			540		0.20	4	
	$J = 2–1$[c]	...	540	0.15	0.15	<10	
^{13}CO	$J = 1–0$	250	550	0.23	0.11	4	0.7
			540		<0.02		
	$J = 2–1$	350	550	0.16	0.05	5	0.4
$C^{18}O$	$J = 1–0$	180	...	0.22	<0.01		

[a] Capital letters in the central velocity column indicate feature designations.

[b] Continuum temperature T_c^* and the negative peak temperature T_{peak}^* of the absorption lines are both antenna temperatures in K not corrected for the main beam efficiencies ($\eta_{115\ GHz} = 0.68$, $\eta_{230\ GHz} = 0.48$; Booth *et al.* 1989).

[c] Data from the Caltech Submillimeter Telescope; Phillips *et al.* 1990.

Hulst, Golish, and Haschick 1983). Line emission from molecular species other than CO is very weak. Upper limits on the HCO^+, HCN, CN, and CS emission are in agreement with a ratio of 10:1 to 20:1 with respect to the $^{12}CO(1–0)$ line intensity, as observed for other galaxies (e.g., Nquyen-Q-Rieu, Nakai, and Jackson 1989; Henkel, Mauersberger, and Schilke 1988).

III. DISTRIBUTION AND KINEMATICS OF THE ABSORBING GAS

In this section we show that the absorption takes place in the same gas that is responsible for the molecular line emission from the dust lane (Paper I; Phillips, Sanders, and Sargent 1989; Israel *et al.* 1990). A comparison to the H I absorption (van der Hulst, Golish, and Haschick 1983) indicate that the absorbing clouds are distributed all along the line of sight through the molecular disk of Centaurus A.

a) How Is the Absorbing Gas Distributed?

Since we have measured the central absorption in the ^{12}CO and ^{13}CO lines we are able to distinguish between two models that may explain the presence of this absorption. These are (see Fig. 2) as follows:

1. Absorption of the continuum emission only by molecular clouds in our line of sight to the compact, nuclear continuum source; and
2. Spatially extended line self-absorption by cold, diffuse foreground molecular gas in addition to absorption of the continuum emission.

The first model is supported by the fact that the absorption features are spatially unresolved. If self-absorption were a major contributor to the observed absorption, then it should still be observed away from the center. Due to the rotation of the galaxy, self-absorbed lines would then also be expected to

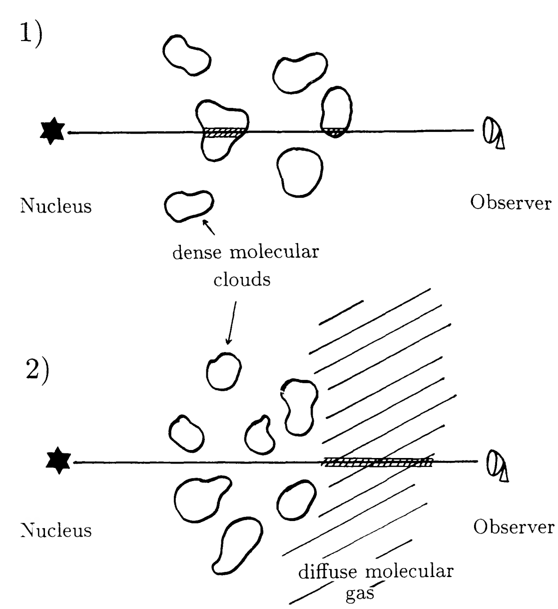

FIG. 2.—Two different models that might explain the absorptions: (1) absorption of the continuum emission only by molecular clouds in our line of sight to the compact, nuclear continuum source; (2) spatially extended line self-absorption by cold, diffuse foreground molecular gas in addition to absorption of the continuum emission. Our data are in favor of the first model.

be considerably broader. Further support for this first model is that the depth of the ^{12}CO absorption is equivalent to the depth of the continuum. This is exactly what is expected for continuum absorption from dense clouds in model 1, whereas it would be somewhat of an odd chance in the second model. Finally, the ^{13}CO absorption is deeper than the line emission, suggesting that it is mostly the continuum radiation that is absorbed. The same is found for the more complex molecular species as well.

As such, the presence of a large amount of cold foreground molecular gas (as implied in model 2) can be ruled out and the absorption features are likely to be due to the same type of clouds that give rise to the CO line emission. We conclude that the absorption features are due to clouds that happen to lie along the line of sight to the nuclear continuum source.

Assuming that the absorption takes place in "normal" molecular clouds, we can now use the data in Table 1 to derive optical depths of individual absorbing clouds. For the central feature A, the depth of the ^{12}CO(1–0) absorption equals the continuum level and appears to be saturated. This indicates optical depths of the order of 2 or larger. The depth of the central ^{13}CO(1–0) absorption is only about 50% of the continuum level indicating an optical depth of $\tau_{13} = 0.7 \pm 0.1$ and hence $\tau_{12} \sim 42$ for a fractional abundance of [^{12}CO]/[^{13}CO] = 60 (Millar and Freeman 1984*a*, *b*; Graedel, Langer, and Frerking 1982; Wannier 1980).

The blueshifted ^{12}CO(1–0) absorption feature B is not saturated but is as deep as the central absorption A and hence the optical depth is larger than 2 as well. Due to the different beam-filling factors of ^{12}CO and ^{13}CO lines (e.g., Martin, Sanders, and Hills 1984), there should also be clouds associated with little if any ^{13}CO absorption, which seems to be the case for feature B; for its ^{13}CO(1–0) absorption, we can give only an upper limit which results in an optical depth of less than 0.1, indicating $\tau_{12} < 6$ for the assumed fractional abundances. The optical depth of the ^{12}CO(1–0) line of the absorbing cloud at 540 km s^{-1} therefore has to be between 2 and 6.

b) Kinematics

From our data there is no indication that these clouds have to be particularly close to the nucleus—they just happen to be in the line of sight toward the nucleus so that they can be taken as representative of the same clouds that give rise to the observed CO emission from Centaurus A. From the emission-line data (Paper I), we infer a velocity dispersion of 60 km s^{-1} in the molecular disk. Observed velocity differences of 60 km s^{-1} between individual absorption-line features are therefore not peculiar. In addition, the central H I absorption feature shows a frequency shift as a function of position against the jet components that is consistent with the rotation curve (van der Hulst, Golish, and Haschick 1983). This indicates that the absorption takes place in clouds *all along* the line of sight through the galaxy. Assuming that the absorbing atomic and molecular gas components are well "mixed" along the line of sight through the molecular disk of Centaurus A, we estimate a *mean distance* of the absorbing material to the nucleus of the order of 1 kpc (the diameter of the molecular disk is about 2.6 kpc; Paper I). The H I absorption line widths (FWHM) are less than 25 km s^{-1}. The width includes a contribution from component B which can be seen in the blue wing of the absorption spectrum shown in Gardner and Whiteoak (1976). The (FWHM) line widths of the different ^{12}CO(1–0) absorption features close to the systemic velocity of Centaurus A range from less than 4 to about 8 km s^{-1}, which is well within the range of line widths derived for single molecular clouds in our Galaxy (Solomon *et al.* 1987). In this scenario it is difficult to distinguish between models in which the absorption feature A is due to one cloud only or several different clouds along the line of sight. In both cases, the narrow CS(2–1) feature may be due to a single cloud or cloud core exhibiting a low velocity dispersion. This complexity of the absorption spectra excludes an explanation of the line widths of different molecular and isotopic species in a framework of a "curve-of-growth" analysis, as applicable to simple line profiles representing the "microturbulence" of homogeneously distributed gas.

IV. PHYSICAL PROPERTIES OF THE ABSORBING GAS

In the following we will discuss molecular excitation and abundances of the absorbing material. For the absorption feature A at the systemic velocity of Centaurus A, the corresponding quantities will be averaged properties of the gas along the line of sight. If feature A is due to several clouds, the properties of these individual clouds may be different.

a) Molecular Excitation

For ^{13}CO we have measured the absorption in both the $J = 1–0$ and $J = 2–1$ line. In both cases the absorption seems to occur in optically thin gas. In the following we will derive physical properties (volume density, column density, and kinetic temperature) of the gas responsible for the central absorption at a velocity of 550 km s^{-1}. Calculations have been carried out for LTE and non–LTE conditions. In both cases, we assume a simple one-component model in which the ^{12}CO and ^{13}CO absorption arises in gas with identical physical conditions.

For the absorption line against the continuum, the main beam brightness temperature can be written as

$$T_{\rm mb} = [J_\nu(T_{\rm ex}) - J_\nu(T_{\rm bg}) - T_{\rm con}](1 - e^{-\tau}) \approx -T_{\rm con}(1 - e^{-\tau}) , \quad (1)$$

where $T_{\rm bg}$ is the cosmic background brightness temperature, $T_{\rm ex}$ is the excitation temperature, and $T_{\rm con}$ is the beam-diluted continuum background. $J_\nu(T)$ is the equivalent Rayleigh-Jeans brightness temperature

$$J_\nu(T) = \frac{h\nu/k}{e^{(h\nu/kT)} - 1} . \quad (2)$$

Assuming *LTE* conditions we can derive an estimate of the excitation temperature $T_{\rm ex}$. For optically thin gas, the ratio of main beam brightness temperatures of the two lines can be written as

$$\frac{T_{\rm mb,\,2-1}}{T_{\rm mb,\,1-0}} = \frac{\tau_{2-1}}{\tau_{1-0}} \frac{T^c_{2-1}}{T^c_{1-0}} . \quad (3)$$

T^c_{1-0}, T^c_{2-1} are the beam-averaged continuum background temperatures at the frequency of the two ^{13}CO lines, and τ_{1-0}, τ_{2-1} are the corresponding line optical depths. In LTE the optical depths are related to each other via

$$\frac{\tau_{2-1}}{\tau_{1-0}} = 2\,\frac{(1 - e^{-10.6/T_{\rm ex}})}{(e^{5.3/T_{\rm ex}} - 1)} . \quad (4)$$

For the ^{13}CO absorption lines, we determine an optical depth ratio of $\tau_{2-1}/\tau_{1-0} = 0.57 \pm 0.1$ and the main beam brightness temperature ratio of $T_{\rm mb,\,2-1}/T_{\rm mb,\,1-0} = 0.63 \pm 0.1$.

Through equations (1)–(3), both values are consistent with an excitation temperature of T_{ex} of 3–4 K. This result is also in agreement with the low upper limit on the CN(2–1)/CN(1–0) absorption-line ratio of 0.3. If the gas is subthermally excited, the kinetic temperature will of course be larger. Since the velocity shift as a function of position in the H I absorption indicates that most of the absorption occurs in the disk, we can compare our temperature estimate with the result obtained from the ^{12}CO emission line ratios off nucleus (Paper I). These range from 0.3 to 0.5 and indicate that the emission comes from very cold ($T_{ex} < 10$ K) or subthermally excited gas which is in agreement with the result obtained above.

In order to take *non-LTE* conditions, clumpiness, and opacity effects into account, we calculated simple one-component models of the absorbing gas as described by Genzel *et al.* (1990) and Eckart *et al.* (1990*b*). We assumed fractional abundances of $^{12}CO/H_2 = 8 \times 10^{-5}$ (§ IV*d*[ii]) and $^{12}CO/^{13}CO = 60$, a line width of a single clump of $\Delta v_{clump} < 2$ km s^{-1} and a macroturbulent velocity width of $\Delta v_{cloud} = 5$ km s^{-1}, so that the total line width for Gaussian velocity distributions is of the order of the observed line width of about 5–6 km s^{-1}. The filling factor velocity interval was set to $F_0 = 0.5$, typical for molecular clouds in our Galaxy. The calculations were carried out assuming that at a mean distance of 1 kpc (see § III*b*) radiative excitation from the nuclear continuum emission is not important for the CO molecules (as indicated in § IV*b*). The calculations result in physical properties (see Fig. 3) of the absorbing molecular gas that are very much comparable to those of the emitting gas in the disk of Centaurus A (Paper I): the kinetic temperature is of the order of 10 K or below, the CO column density is of the order of (3–5) $\times 10^{17}$ cm^{-2}, and volume densities are 10^4 cm^{-3} or higher. The temperature and column density are in good agreement with the LTE calculations. The range of volume densities suggested by the calculations indicates that the densities are spread around the critical density of 2×10^4 cm^3 required to populate the $J = 2$ level. For the weak, broad, redshifted absorptions, multiline data, which would allow us to investigate the physical properties of the gas, are not yet available.

b) Influence of the Compact Nucleus on Excitation

The kinetic temperature of the absorbing gas is consistent with heating via cosmic rays. As shown by many authors (e.g., Goldsmith and Langer 1978; de Jong, Dalgarno, and Boland 1980), a cosmic-ray ionization rate of $\sim 5 \times 10^{-17}$ s^{-1} suffices to heat the gas in dense molecular clouds up to about 10 K. However, cosmic-ray heating is not the only heating mechanism that has to be considered. Other possible mechanisms are collisional heating by dust (Paper I) and radiative heating by star-forming regions or by an active nucleus. While the HCN hyperfine structure line ratios indicate that in the case of Centaurus A heating by active star-forming regions is probably not important for the excitation of the absorbing molecular gas (§ IV*c*), we have to consider possible excitation from the nucleus. For any cloud at a reasonable distance from the active core, UV heating from the nonthermal nucleus can be excluded, due to the small angle of the core and especially the high UV extinction of the dense clouds.

In this section we check whether, for the central CO isotopic absorption lines, our results on the molecular excitation in § IV*a* are consistent with (*a*) the assumed distance range of the absorbing clouds from the nucleus (see § II*b*), (*b*) limits on the

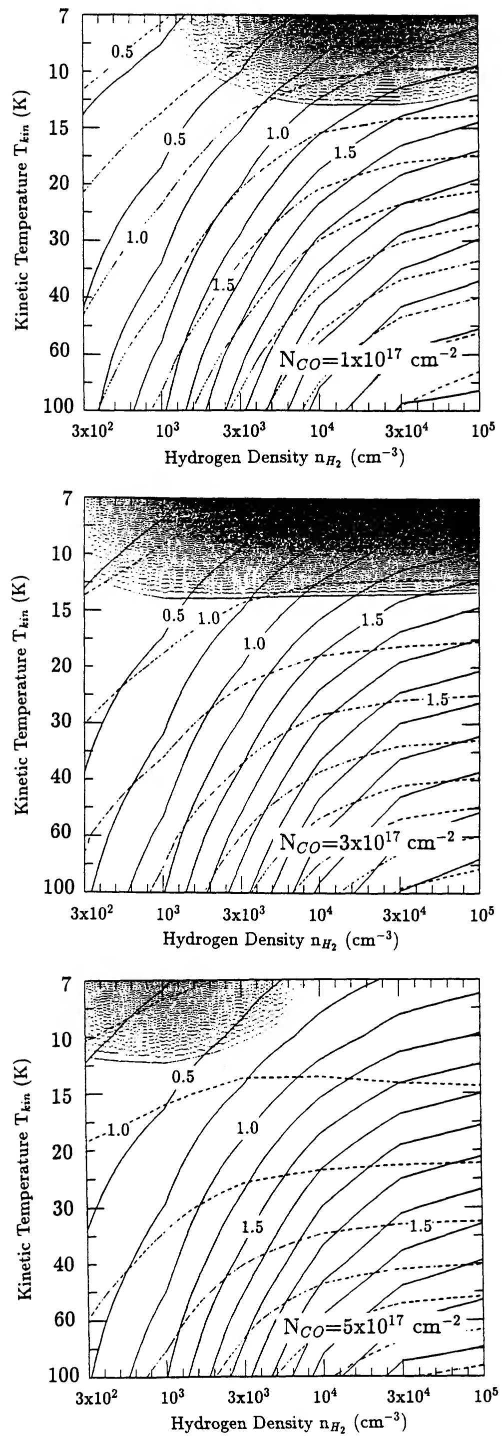

FIG. 3.—Constraints on the one-component model parameters for the central CO absorption at 550 km s^{-1} toward Centaurus A. For line-averaged ^{12}CO column densities N_{CO} of 1×10^{17}, 3×10^{17}, and 5×10^{17} cm^{-2}, two line ratios are plotted vs. molecular hydrogen density, n_{H_2}, and kinetic temperature, T_{kin}. Broken contours are the ^{12}CO(2–1)/^{12}CO(1–0) ratio, and continuous contours are the ^{13}CO(2–1)/^{13}CO(1–0) ratio. Gray shading is proportional to exp $(-\chi^2)$, χ^2 being calculated from the predicted and measured ratios and intensities and their errors. For isotopic abundances commonly found in Galactic clouds, the most probable values are $N_{CO} = 3 \times 10^{17}$ cm^{-2}, $T_{kin} < 10$ K, and n_{H_2} is of the order of the critical density of 2×10^4 cm^{-3} to populate the CO $J = 2$ level or larger.

size, and (*c*) the brightness temperature of the nonthermal nuclear source. The solid angle Ω under which the compact nuclear nonthermal source of diameter S at a distance D is seen can be calculated as

$$\Omega \approx \pi \arctan^2\left(\frac{S}{2D}\right) \approx \frac{\pi S^2}{4D^2} . \quad (5)$$

Since it is the 4π averaged radiation field that is important for the excitation of molecules at that distance, this results in a dilution factor f of

$$f = \frac{\Omega}{4\pi} \approx \frac{S^2}{16D^2} . \quad (6)$$

Therefore the brightness temperature T_B of the nuclear source results in a diluted continuum temperature T_{con} seen by the molecules of

$$T_{con} \approx T_B \frac{S^2}{16D^2} e^{-\tau_{line}} . \quad (7)$$

Here τ_{line} is the optical depth of the molecular material between the molecule and the continuum source. Table 1 shows that in the case of Centaurus A τ_{line} is typically of the order of 1.0. As indicated by our data, the continuum spectrum of Centaurus A is flat between a wavelength of 1 and 3 mm. At centimeter and millimeter wavelengths it has been shown that compact cores of flat spectrum extragalactic radio sources radiate at the inverse Compton limit and have Rayleigh-Jeans brightness temperatures of the order of 10^{12} K (Kellermann and Pauliny-Toth 1969; Krichbaum *et al.* 1990; Bååth *et al.* 1990), whereas those of optically thin jet components that are extended in the milliarcsecond domain are of the order of 10^9 K (see also Eckart *et al.* 1987). The variablity at millimeter wavelengths observed by Kellermann (1974) suggests a size of the compact core of about a light-day which is well in agreement with limits on the centimeter-wavelength core component size implied by VLBI measurements (Meier *et al.* 1989; Shaffer and Schilizzi 1975; Kellermann 1974). Combined with the main beam efficiency of 68%, the measured continuum level of $T_A^* = 0.22$ K results in an estimate of the brightness temperature of the nonthermal nucleus of 4×10^9 K. At an assumed average distance of about 1 kpc (see § III*b*), this gives a continuum brightness temperature seen by the molecules of about 4×10^{-3} K. The full range of reasonable core brightness temperatures of 10^9–10^{12} K translates into a range of diluted main beam continuum temperatures T_{con} of 10^{-3} to 3 K. This makes it appear very unlikely that radiative excitation by the nuclear continuum emission is important for the molecular gas responsible for the absorption feature A at the systemic velocity of Centaurus A.

c) Hyperfine Structure Line Ratios in HCN *and* CN

The hyperfine structure of the HCN(1–0) and the CN(1–0) absorption provide us with further information on density, clumpiness, and type of clouds in which the absorption takes place. For the LTE case of optically thin absorbing clouds, the intensity ratio of the hyperfine components are expected to be $R_{12} = I_{F=1-1}/I_{F=2-1} = 0.6$ and $R_{02} = I_{F=0-1}/I_{F=2-1} = 0.2$ (Walmsley *et al.* 1982). The HCN(1–0) spectrum clearly shows anomalous hyperfine structure line ratios. From the absorption spectrum in Figure 1 we measure $R_{12} = 0.8 \pm 0.1$ and $R_{02} = 0.9 \pm 0.1$, which is clearly not in agreement with the optically thin LTE ratios. The situation is more complicated, since there is a considerable amount of absorption blueshifted from the main features (corresponding to feature A in the HCO^+ spectrum). This may be due to material responsible for the strong secondary absorption feature B seen in the ^{12}CO and HCO^+ spectrum. In both cases the secondary line is offset by about 10 km s^{-1} from the central feature A. For the HCN absorption this implies at least a partial overlap of the $J = 1$–0, $F = 0$–1 line of component A with the $J = 0$–1, $F = 1$–1 line of component B. The possible influence of the very narrow feature C mentioned in § II*a* may complicate the situation even further. The line overlaps of the different hyperfine structure components may have an influence on the populations per sublevel of the $J = 1$–0 line of the central feature. However, since hyperfine structure lines overlap only partially and the integrated secondary line intensities are almost one order of magnitude weaker than the central features of component A, we simply apply a zero-order correction for additional absorption from the blueshifted components and find that the ratio R_{02} may be as low as 0.5. In Figure 4 R_{12} and R_{02} for different Galactic clouds are compared.

The mere presence of hyperfine structure anomalies limits the density to less than the critical density of about 4×10^6 cm^{-3} for the HCN(1–0) line (Green and Thaddeus 1974). For the range of hyperfine ratios derived above and a column density of approximately 6×10^{13} cm^{-2} (§ IV*d*[i]), radiative transport model calculations (Hafener 1985) indicate a kinetic temperature of $T_{kin} \leq 20$ K and hydrogen densities of $10^{6 \pm 0.5}$ cm^{-3}. The fact that this hydrogen density is larger than the density of a few times 10^4 cm^{-3} derived from the CO isotopic data (§ IV*a*) indicates that the absorbing molecular clouds are clumped. Furthermore, the location of Centaurus A in Figure 4 suggests that the absorption is probably more due to cold,

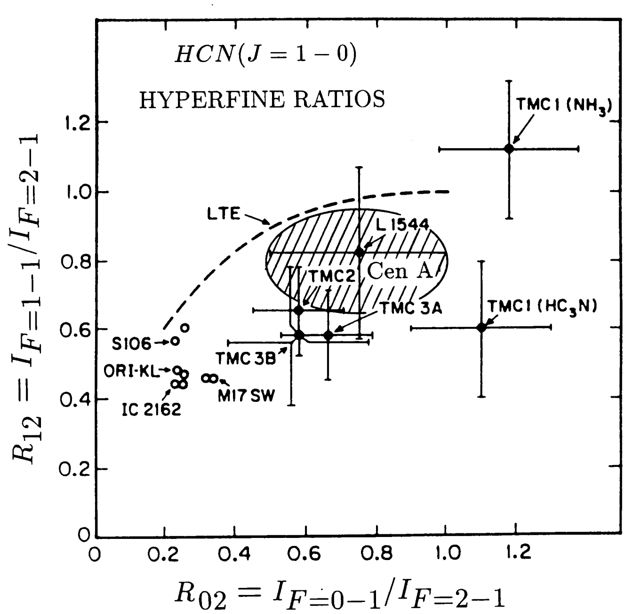

FIG. 4.—The measured intensity ratios R_{12} and R_{02} of hyperfine line components of HCN (Walmsley *et al.* 1982). Cold, dark clouds are indicated by filled circles; warm clouds associated with H II regions are indicated by open circles. The position of the absorbing material toward the nucleus of Centaurus A is indicated by the shaded area.

dark clouds, rather than warm clouds associated with H II regions.

Towards Centaurus A, the ratio of the two strongest hyperfine components of the CN(1–0) line, $R_{CN} = (I_{F=5/2-3/2})/(I_{F=3/2-1/2})$, is observed to be 1.5. In the LTE case this ratio should correspond to 2.7 (Churchwell and Beiging 1983). Such behavior of the line intensities has been observed, in emission, toward various dark clouds in the Galaxy and has generally been attributed to self-absorption by cooler foreground gas. In summary, the HCN and CN hyperfine line ratios indicate that the absorbing gas is clumped and cold.

d) Abundances

In this section we will first outline the formalism to obtain column densities from the absorption data. We will estimate the $[^{12}CO]/[H_2]$ ratio for the absorbing gas, then calculate fractional abundances relative to H_2, and compare the results with values obtained for other galaxies.

i) *Molecular Column Densities*

For the small beam-filling factors of the milliarcsecond continuum source and the absorbing column of molecular gas, equation (1) yields

$$\tau = -\ln\left(1 + \frac{T_{mb}}{T_{cont}}\right) . \tag{8}$$

Assuming LTE conditions estimates of the column density N can then be derived via

$$N = \frac{8\pi\nu^3}{c^3 A_{ul} g_u} \frac{Q(T)e^{E_l/kT}}{1 - e^{-h\nu/kT}} \int \tau\, dv , \tag{9}$$

where g_u is the statistical weight of the upper level, E_u is the energy of the upper level, A_{ul} is the Einstein A-coefficient, and $Q(T)$ is the partition function. Assuming a Boltzmann-distributed population, we use

$$Q(T) = \sum_{J=0}^{\infty} (2J + 1) \exp\left[-hBJ(J + 1)/kT\right],$$

where B is the molecular rotation constant. However, model calculations of the molecular excitation of CO emission and absorption lines indicate that the gas is subthermally excited and that the density is of the order of the critical density of the $J = 2$ level. To take this fact into account, we simply assume for all molecular species measured that only the first two levels are populated and that the population of all higher rotational levels is negligible for the bulk of the absorbing molecular gas.

For the $^{13}CO(1–0)$ line we obtain a column density of $N_{^{13}CO} = 10^{16.2}$, which is a factor of 2.8 larger than the value implied by the beam-averaged ^{12}CO column density obtained from the emission lines and the model calculations described in Paper I. Such discrepancies are expected, since the molecular interstellar medium is probably highly clumped.

ii) *The ^{12}CO Abundance*

It is initially not clear whether the ^{12}CO absorption takes place in diffuse or dense molecular clouds and since we want to derive fractional molecular abundances relative to H_2, it does not appear to be adequate to assume a $^{12}CO/H_2$ ratio that can vary by two orders of magnitude between the diffuse and dense cloud case (Graedel, Langer, and Frerking 1982). Instead we assume a $^{12}CO/^{13}CO$ isotopic ratio that is known to vary only by a factor of a few in Galactic clouds (assumed to be 60; Millar and Freeman 1984*a*, *b*; Graedel,Langer, and Frerking 1982; Wannier 1980) and estimate the ^{12}CO fractional abundance from the column densities of ^{13}CO and H I from the absorption lines, inferring the visual extinction from the 9.7 μm silicate absorption feature (Grasdalen and Joyce 1976). Again, we assume that the atomic and molecular gas and the dust are well mixed along the line of sight through the galaxy.

The visual extinction A_V can be written as a function of the $[^{12}CO]/[^{13}CO]$ ratio, $X_{12/13}$, the $[H_2]/[^{12}CO]$ ratio, $X_{H2/12}$, as well a the H I spin temperature T_S:

$$A_V = 5.5 \times 10^{-22}[N_{H\,I} + 2N_{^{13}CO} X_{12/13}/X_{H2/12}] \tag{10}$$

with

$$N_{H\,I} = 1.8 \times 10^{18} T_S \int \tau\, dv . \tag{11}$$

For the central absorption in H I van der Hulst, Golish, and Haschick (1983) find

$$N_{H\,I} = 3 \times 10^{19} T_S \text{ cm}^{-2} . \tag{12}$$

The spin temperature can range between 80 K, according to the standard interpretation of the H I emission in the Galaxy (Kulkarni and Heiles 1988), and a value of the order of 200 K, if a large fraction of H I emission originates in warm, dense photodissociation regions at the surfaces of molecular clouds (Eckart *et al.* 1990*b*; Shaya and Federman 1987). The HCN hyperfine structure lines rule out the presence of large amounts of absorbing warm gas directly associated with star-forming regions. Therefore, in the following we have used the value of 80 K for the spin temperature. For the given H I column densities A_V is then mainly a function of the $[^{12}CO]/[H_2]$ ratio, and for a known A_V equation (10) can be used to derive the mean ^{12}CO abundance along the line of sight toward the nucleus of Centaurus A.

The visual extinction can be inferred using the 9.7 μm silicate absorption feature (Grasdalen and Joyce 1976) and the interstellar extinction to optical depth ratio (Rieke and Lebofsky 1985). Grasdalen and Joyce find the optical depth of the silicate feature to be $\tau_{Si} = 0.9 \pm 0.2$. Combined with $A_V/\tau_{Si} = 16.6 \pm 2.1$ (Rieke and Lebofsky 1985), we obtain $A_V = 15 \pm 5$ mag. Equation (10) then results in a ^{12}CO abundance ranging between (5 and 11) $\times 10^{-5}$, which is well in agreement with 8×10^{-5}, a typical value for the dense molecular interstellar medium in the Galaxy.

iii) *Molecular Fractional Abundances*

Using a $^{12}CO/^{13}CO$ isotopic ratio and the $^{13}CO(1–0)$ column density obtained from the absorption, we can calculate an H_2 column density for the absorbing material and therefore derive abundances for the other molecular species we observed in absorption. As determined from the $^{13}CO(2–1)$ to $^{13}CO(1–0)$ absorption-line ratio and our model calculations, we assumed an excitation temperature between 6 and 10 K. In Table 2 we compare the abundances we obtained with the results of model calculations, for the case of both dense and diffuse Galactic clouds. We note that from the data collected in Table 2 by itself, it is not possible to distinguish between the dense and diffuse cloud case.

In columns (6) and (7), we list the abundances obtained via equation (9) assuming $^{12}CO/H_2$ ratios of 8×10^{-5} and 3×10^{-7}, typical for Galactic dense and diffuse clouds, respectively. In both cases, the obtained values agree reasonably with measurements and model calculations of the different cloud types. Since the $^{12}CO/H_2$ ratio for the absorbing gas derived from equation (10) using the visual extinction argument presented above is in good agreement with the value obtained for

TABLE 2

COMPARISON OF DERIVED ABUNDANCES OF MOLECULAR SPECIES IN CENTAURUS A WITH MODEL CALCULATIONS FOR MOLECULAR CLOUDS

MOLECULAR SPECIES (1)	DIFFUSE CLOUDS[a] (2)	DENSE CLOUDS[b] (3)	LOW METALLICITY[c] (4)	HIGH METALLICITY[c] (5)	CENTAURUS A (6)	CENTAURUS A (7)
^{12}CO	−7.0 to −6.4	−3.9 to −3.4	−4.0	−5.0 to −4.0	**−4.1**	**−6.5**
^{13}CO	−8.5 to −8.2	...	...	...	−5.9	−8.3
HCO^+	−11 to −10	−8.2 to −8.0	−8.3 to −7.6	−11.1 to −10.1	−8.1	−10.5
HCN	−11 to −10	−6.9	−8.3 to −8.0	−8.9 to −7.9	−8.3	−10.7
CN	...	−8.0 to −7.6	−10.3 to −7.9	−9.9 to −6.2	−7.5	−9.9
CS	...	...	−9.3 to −8.9	−7.5 to −6.2	−8.6	−11.1

NOTE.—Listed are ranges and approximate values of decadic logarithms of the molecular abundances relative to molecular hydrogen. Cols. (2)–(5) summarize theoretical values for dense and diffuse Galactic molecular clouds. Col. (6) gives abundances assuming a ^{12}CO abundance of 8×10^{-5} a typical value for Galactic dense molecular clouds. For comparison col. (7) gives the abundances assuming a ^{12}CO abundance 3×10^{-7}, a typical value for Galactic diffuse molecular clouds. Further values derived are uncertain by at least a factor of 2 (see text).

[a] van Dishoeck and Black 1986 for ζ Per, χ Oph, ρ Oph, and o Per.

[b] Millar and Freeman 1984*a*, *b* for TMC 1 and L183.

[c] Graedel, Langer, and Frerking 1982 for $T = 10$ K and densities of 10^3–10^5 cm^{-3}.

dense Galactic clouds, column (6) represents the abundances for the different molecular species in Centaurus A. Due to the uncertainty in the determination of A_V and T_s the uncertainties in abundances quoted in column (7) are of the order of 50%. Our estimates of density and abundances indicate that the absorption takes place in cold, dense molecular clouds rather than in the diffuse, low-density interstellar medium of Centaurus A.

In Table 3 we compare the molecular abundances of four galaxies. The data for sources other than Centaurus A have been calculated from emission lines. The values spread over about two orders of magnitudes. The values for Centaurus A are right in the range covered by other well-studied galaxies.

V. CONCLUSION

The main results on the properties of the absorbing molecular gas in Centaurus A can be summarized as follows:

1. The CO emission and absorption-line ratios as well as the comparison to the H I data indicate that the absorption takes place against the compact nuclear continuum source in the line-emitting clouds all along the line of sight through the molecular disk of Centaurus A. A mean distance of the clouds responsible for the central absorption feature at the systemic velocity of Centaurus A is therefore of the order of 1 kpc.

2. For the central absorption at the systemic velocity of Centaurus A, the CO line ratios indicate that the bulk of the absorbing gas is cold with $T_{kin} < 10$ K.

3. Estimated ^{12}CO abundances of a few times (5–11) $\times 10^{-5}$ relative to H_2 as well as half-power line widths of about 6 km s^{-1} for the absorption at the systemic velocity of Centaurus A are comparable to typical values found for dense Galactic molecular clouds.

4. Abundances, excitation temperature, and density of the absorbing and emitting molecular gas in the disk of Centaurus A are similar to the values obtained from the disk material in other galaxies. The number density of molecular hydrogen is of the order of the CO critical density of the $J = 2$ rotational level (2×10^4 cm^{-3}).

5. The HCN and CN lines indicate that the absorbing molecular clouds are clumped. The hyperfine structure line ratios and the column density are consistent with a number density close to 10^6 cm^{-3} and a kinetic temperature of less than 20 K.

6. The fact that the absorbing molecular gas is cold and dense is in agreement with the finding that at the mean distance of the absorbing gas of 1 kpc radiative excitation from the nuclear source is not important.

7. Molecular abundances relative to H_2 for CO, HCO^+, HCN, CN, and CS in Centaurus A are within the same range of values obtained from other well-studied galaxies.

TABLE 3

COMPARISON OF ABUNDANCES OBTAINED FOR DIFFERENT GALAXIES

Species	NGC 253	IC 342	M82	Galaxy	Centaurus A
HCO^+	≤ -10[a]	...	≤ -9.4[a]	−8.2[e]	−8.1
HCN	≤ -10[a]	...	≤ -9.4[a]	−7.5[e]	−8.3
CN	−8.7[b,d]	−8.9[b,d]	−9.7[b,d]	−7.5[e]	−7.5
CS	−7.5[c,d]	−8.7[c,d]	−8.8[c,d]	−9.0 to −7.8[b]	−8.6

NOTE.—Listed are decadic logarithms of the molecular abundances relative to molecular hydrogen. For NGC 253, IC 342, and M82, the molecular abundances are derived from emission-line data.

[a] Nguyen-Q-Rieu, Nakai, and Jackson 1989. Face-on column densities are obtained via $N_{H_2} = 4 \times 10^{20} I^*_{CO} \cos(i)$, i being the inclination of the galaxies.

[b] Mauersberger, Henkle, and Schilke 1989.

[c] N_{H_2} taken from Canzian *et al.* 1988 for NGC 253, Eckart *et al.* 1990*b* for IC 342, and Lo *et al.* 1987 for M82.

[d] Mauersberger and Henkle 1989.

[e] Average value for Orion, Sgr B2, and TMC 1 taken from Walmsley 1985.

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