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H₂ emission and CO absorption in Centaurus A⋆:
evidence for a circumnuclear molecular disk

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Abstract. We have detected several molecular emission lines ($H_2 \, v = 1-0 \, S(1), S(0), Q(1), Q(3)$; $J = 1-0 \, {}^{12}CO$; ${}^{13}CO$) towards the core of Centaurus A (NGC 5128). We also detected CO absorption features coincident with known H I, C_3H_2 and H_2CO absorption lines. CO to H I optical depths are high for blueshifted gas but low for redshifted gas. The intensity ratio of ${}^{12}CO/{}^{13}CO$ emission of about ten implies a mass $M(H_2)$ of order $10^8 \, M_\odot$ within a 40″ beam; CO emission is consistent with an excitation temperature $T_{ex} = 10$ K, while CO absorption appears to have a higher excitation temperature.

The H_2 emission originates in an unresolved nuclear source (size $< 4″$, corresponding to < 95 pc). It appears to be collisionally excited; the shocked H_2 may mark the inner edge of a cavity in the CO distribution.

Literature data, combined with the new observations, suggest that the nucleus of Cen A is surrounded by a disk of mass $2 \, 10^7 \, M_\odot$. A disk with outer edge at $r = 160$ pc, a thickness of 80 pc, a cavity with radius 40 pc, and with a density distribution of $n \sim r^{-2}$ is consistent with all existing observations.

Key words: extragalactic: Centaurus A – NGC 5128; molecules: H_2 – CO – CO absorption; galaxies: nuclei – circumnuclear disk

1. Introduction

NGC 5128 is among the brightest galaxies in the sky and has the appearance of an elliptical galaxy, crossed by a broad, patchy band of dark matter. Optical observations have been discussed by Graham (1979), Phillips (1981), Ebneter and Balick (1983). NGC 5128 also contains the nearby strong extragalactic radio source Centaurus A which has a rather complex structure (cf. Schreier et al., 1981; Meier et al., 1988). Dust-to-gas ratios appear to be in harmony with those in the Solar Neighbourhood (Van Gorkom, 1987). For consistency with earlier publications, we adopt a distance of 5 Mpc throughout this paper, although recent determinations favor a smaller value (Frogel et al., 1987; Harris et al., 1984).

The nucleus is a strong infrared emitter (Becklin et al., 1971; Kunkel and Bradt, 1971; Grasdalen and Joyce, 1976; Giles, 1986; Joy et al., 1988; Marston and Dickens, 1988) with dust temperatures of 30–40 K and a luminosity of about $1.5 \, 10^9 \, L_\odot$, most likely due to thermal emission from dust close to the nuclear power source (Joy et al., 1988). VLBI measurements of the nucleus show a very compact ($0″.5 \, 10^{-3}$) core, which is self-absorbed at frequencies below 8 GHz ($\alpha > 0.5$; $S_\nu \sim \nu^\alpha$), and a more extended ($100″ \, 10^{-3}$) jet ($\alpha = -0.77$) with structure on scales of $10″ \, 10^{-3}$ (Meier et al., 1988). The core emission is variable and has a steep, rising spectrum above 10 GHz (e.g. Kellerman, 1974; Abraham et al., 1982).

With high spatial resolution, Van der Hulst et al. (1983) observed three discrete and narrow H I absorption features against the nucleus. The strongest of these is also seen against the inner jet up to 30″ (corresponding to 725 pc) away from the nucleus. Molecules such as OH, H_2CO, C_3H_2 have also been seen in absorption against the nucleus (Gardner and Whiteoak, 1976a,b; Bell and Seaquist, 1988).

We included NGC 5128 in our program to study H_2 and CO in nuclei of galaxies with strong near-infrared emission, as we deemed it important to obtain constraints on the physical parameters of molecular material close to the nucleus of this unusual galaxy. In particular, we were interested to see whether the abundant CO molecule could likewise be seen in absorption. Here we report the results.

2. Observations

2.1. H₂ observations

The H_2 observations were made in March 1988 with the ESO infrared cooled grating spectrometer (IRSPEC) on the 3.6 m telescope at La Silla (Chile). IRSPEC allows simultaneous observations of 32 channels in a nominal 6″ aperture with a spectral resolution of about 900; details have been given by

Moorwood et al. (1986). Calibration and correction for atmospheric attenuation were determined in the usual manner by observing the standard stars HR 2290 ($K = 5.15$, G3 V), HR 4523 ($K = 3.32$, G5 V) and HR 6072 ($K = 1.64$; G8 III) (Koornneef, 1983). The three calibrations differed by at most 10%. Under moderately good seeing conditions, we observed several positions towards the nucleus at the wavelength of the $v = 1 - 0$ $S(1)$ line of excited H_2 (2.122 μm). We used a beam-switching mode with a north-south throw of 40″, well away from the nucleus, but within the optical image of the dark band.

H_2 emission was detected only from the nuclear radio position (Fig. 1). The positioning of the slit on the nucleus was accurate to about 1″. Positions offset by 5″ from the nucleus in all directions did not show measurable H_2 emission, except perhaps for a marginal signal 5″ south. Thus, the detected H_2 cloud is essentially unresolved ($< 4″$, i.e. < 95 pc). In contrast, the 2 μm continuum was found to be extended over at least 10″ (240 pc), consistent with the measurements by Giles (1986). As shown by Giles, the positions of the nucleus at infrared and radio wavelengths differ from that of the visible 'nucleus' owing to a strong gradient in extinction. On the nuclear position we also obtained spectra at the wavelengths of other K-band H_2 transitions, detecting the $1 - 0$ $S(0)$, $1 - 0$ $Q(1)$ and $1 - 0$ $Q(3)$ lines. The

results are summarized in Table 1 and shown in Fig. 1. Unfortunately, the spectral setting was such that the intensities of the $1 - 0$ $S(1)$ and $1 - 0$ $Q(3)$ lines are divided over two pixels. A short test spectrum with the setting shifted by half a pixel showed that the $1 - 0$ $S(1)$ line then falls in only one pixel, implying that it is unresolved. Note that the line to continuum ratio of the $1 - 0$ $S(1)$ H_2 signal shown in Fig. 1 is only 20%, even at the high spectral resolution of IRSPEC.

2.2. CO observations

The $J = 1 - 0$ CO observations were made in May 1988 and in January 1989 with the 15 m Swedish-ESO Submillimetre Telescope (SEST) at La Silla, Chile. The Schottky diode receiver yielded SSB temperatures of 300 K and 270 K at the observing frequencies of 115 (^{12}CO) and 110 (^{13}CO) GHz, respectively. Overall system temperatures, including the sky, were 650 and 450 K respectively. For a backend, we used a wide band acousto-optical spectrometer of 1000 channels, with a resolution of a 1 MHz (2.6 km s^{-1}) per channel. SEST resolution (FWHP) is 40″ (965 pc) at 110–115 GHz. The observations were made by beam-switching at a frequency of 6 Hz and a throw of 12′, i.e. well clear of the optical image of the galaxy. Towards the nucleus, a ^{12}CO
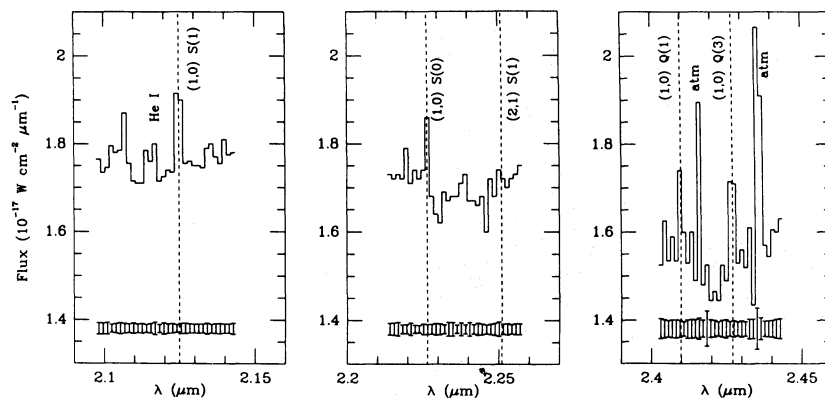

Fig. 1. IRSPEC K-band spectrum of the nucleus of NGC 5128 Transitions listed in Table 1 are identified. The position of the He I 2.113 μm line is indicated, but no detection is claimed. The feature at 2.107 μm appears to be real but is unidentified. Note strong continuum. The systemic velocity corresponds to a wavelength shift of 0.0039 μm

Table 1. IRSPEC H_2 Results on Centaurus A nucleus

Transition	Wavelength (μm)	Continuum flux density[a] (10^{-10} erg s^{-1} cm^{-2} μm^{-1})	Line flux[a] (10^{-14} erg s^{-1} cm^{-2})
$1 - 0$ $S(2)$	2.034	1.9 ± 0.05	≤ 1.0
$1 - 0$ $S(1)$	2.122	1.75 ± 0.05	4.2 ± 0.5
$2 - 1$ $S(2)$	2.154	1.7 ± 0.05	≤ 1.0
Br-γ	2.17	1.7 ± 0.05	≤ 1.2
$1 - 0$ $S(0)$	2.223	1.7 ± 0.05	2.0 ± 1.0
$2 - 1$ $S(1)$	2.248	1.7 ± 0.05	≤ 1.3
$1 - 0$ $Q(1)$	2.407	1.55 ± 0.05	3.6 ± 1.0
$1 - 0$ $Q(2)$	2.413	1.55 ± 0.05	≤ 0.8
$1 - 0$ $Q(3)$	2.424	1.55 ± 0.05	3.6 ± 1.0
$1 - 0$ $Q(4)$	2.437	1.55 ± 0.05	≤ 1.0

[a] Observed values, not corrected for extinction. See text for magnitude of reddening corrections

profile was obtained with a total integration time of 96 min (half of this on-source), and a ^{13}CO profile with a total integration time of 236 min. In addition, we obtained five 24 min ^{12}CO integrations, three along the major axis of Cen A, and two on the minor axis.

Emission at ^{12}CO was readily detected, but emission at ^{13}CO is quite weak. The results are shown in Fig. 2, and listed in Table 2. In the following, we will quote main-beam brightness temperatues T_{mb} (cf. Eckart et al., 1989); at the observing frequency, the main-beam efficiency is 0.62. Towards the nucleus, peak ^{12}CO emission is $T_{mb} = 445 \pm 15$ mK and has a FWHM of 140 ± 10 km s^{-1}. In addition, there is a significant continuum. The continuum source is unresolved; at these high frequencies it
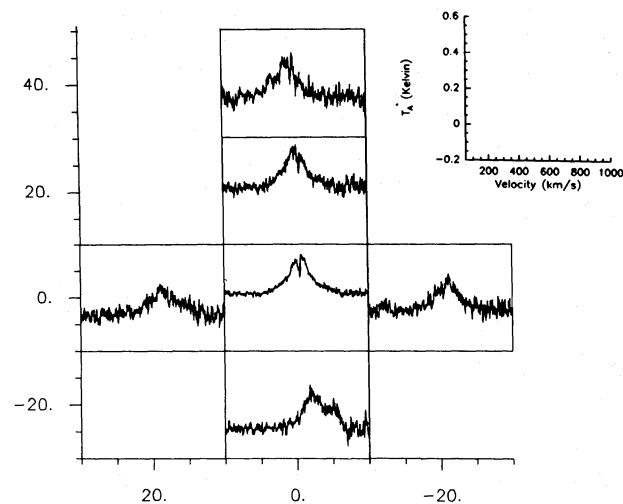

Fig. 2. SEST ^{12}CO spectra towards the central regions of NGC 5128; the spectra form a cross with arms along the major and minor axes respectively. Note enhanced continuum and strong absorption at the central position. Also note that the CO emission central velocity changes along major axis due to rotation, while the absorption is at constant velocity. Temperatures are given as $0.62 \, T_{mb}$

can only be due to the compact 0.5" 10^{-3} radio core. The major axis position 19".5 east-southeast of the nominal center position yielded an almost identical spectrum. This indicates that the true nucleus position is in between; the discrepancy is probably due to (absolute) pointing errors. By interpolation, we find a continuum temperature $T_{mb} = 485 \pm 35$ mK for the nucleus at 115 GHz. Along the major axis, peak ^{12}CO emission is almost constant, while it drops slightly along the minor axis. The single ^{13}CO profile was taken towards the estimated actual nucleus position; it has $T_{mb} = 36 \pm 6$ mK and within the errors the same FWHM.

A remarkable feature of the CO spectra is the deep and narrow absorption at $V_{LSR} = 552$ km s^{-1}. At this velocity, absorption is also seen in the ^{13}CO spectrum. Note that the absorption feature is at a fixed velocity; it does not follow the position-dependent velocity shifts of the ^{12}CO emission (Fig. 2). In Fig. 3 we show the central ^{12}CO and ^{13}CO profiles, as well as our best estimate of the absorption spectrum based on empirical fits of the observed emission line profile (also indicated). Absorption line parameters are included in Table 2.

3. Analysis

3.1. Evidence for a circumnuclear disk in Centaurus A

Before discussing the implications of our H$_2$ and CO observations, we find it useful to consider the implications of existing information on the central region of NGC 5128. Far-infrared observations show a strong unresolved source ($<16''$, i.e. <400 pc FWHM) coincident with the radio nucleus (Joy et al., 1988). Assuming a dust emissivity λ^{-1}, $T_d = 43$ K and a gas-to-dust ratio of 100 by mass, we find a mass $M_H = 1.2 \, 10^7 \, M_\odot$ within 200 pc from the nucleus. If instead we assume a dust emissivity λ^{-2}, we would obtain $T_d = 35$ K, and a mass $M_H = 2.7 \, 10^7 \, M_\odot$. We will assume $M_H = 2 \, (\pm 1) \, 10^7 \, M_\odot$.

The column density through this cloud can be estimated from extinction measurements. From the 9.7 μm silicate absorption strength (Grasdalen and Joyce, 1976) and the interstellar reddening law of Rieke and Lebofsky (1985) we find the extinction to the nucleus to be $A_V = 15 \pm 4$ mag, if there is no silicate in emission.

Table 2. Sest CO results on Centaurus A nucleus

Transition	Type	T_{mb}^a (mk)	ΔV^b (km s^{-1})	V_{Hel}^c (km s^{-1})	Optical depth^d
^{12}CO 1[0	Emission	445 ± 15	140 ± 5	548 ± 4	—
	Absorption	-285 ± 15	6 ± 1.5	550 ± 3	1.4 ± 0.2
	Absorption	-145 ± 15	10 ± 3	538/542	0.48 ± 0.07
	Absorption	-30 ± 15	—	520:	0.08 ± 0.04
^{13}CO 1[0	Emission	36 ± 6	140 ± 15	554 ± 15	0.09 ± 0.02
	Absorption	-64 ± 8	5 ± 2	552 ± 4	0.22 ± 0.03
	Absorption	-20 ± 8	—	540 ± 5	0.065 ± 0.025
Continuum	115 GHz	380 ± 5			
	110 GHz	319 ± 5			

^{a} Main beam brightness temperature
^{b} Corrected for finite velocity resolution
^{c} $V_{Hel} = V_{LSR} - 2.1$ km s^{-1}
^{d} Assuming feature to be resolved in velocity, absorbing material to cover continuum source completely, and emission from the absorbing material to be negligible (see Sect. 3.4.1)
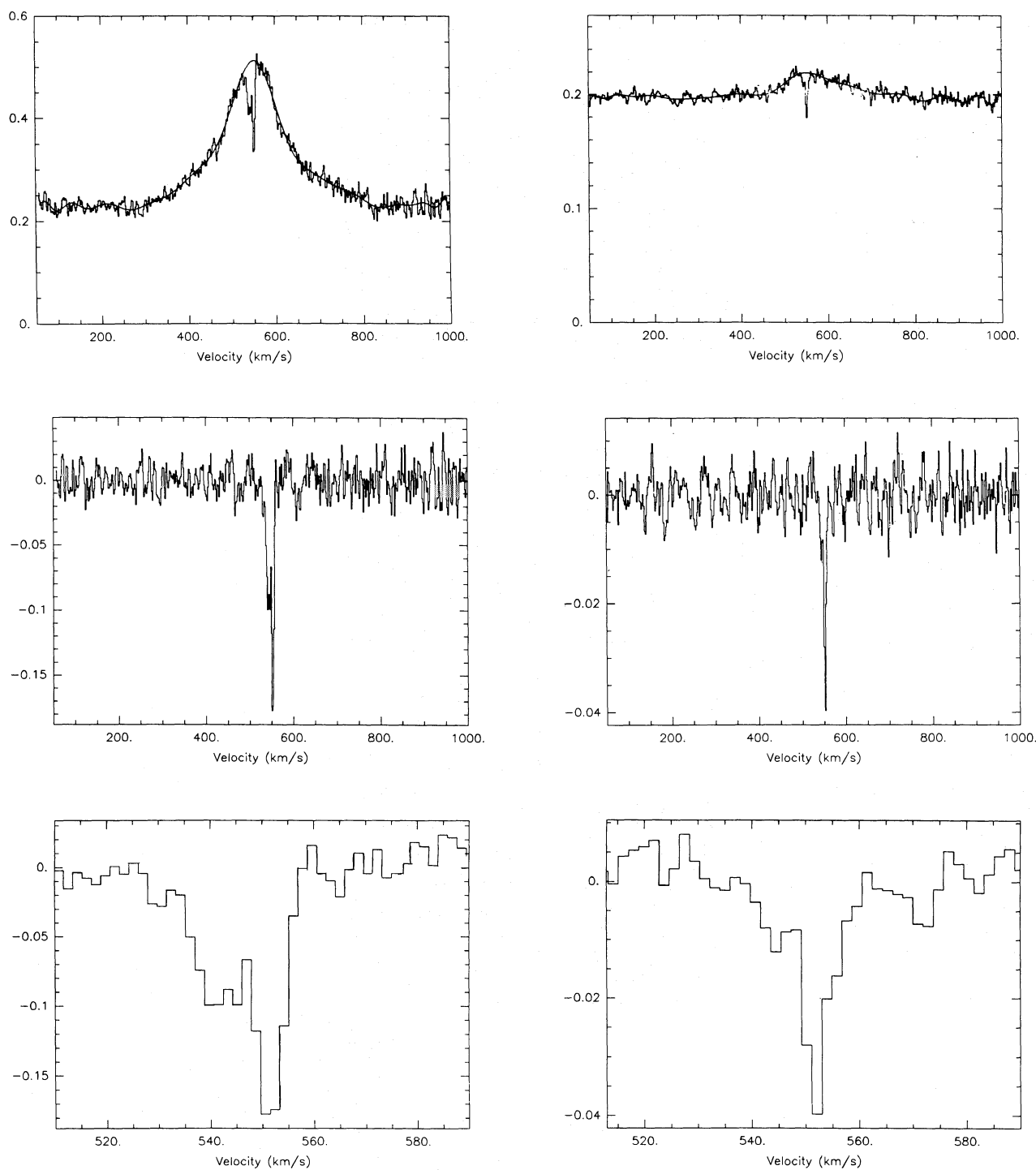
Fig. 3. SEST CO spectra towards the nucleus of NGC 5128. *Top left*: Observed ^{12}CO spectrum with model fit. Note strong continuum. *Middle left*: ^{12}CO absorption spectrum obtained by subtracting fitted emission line from observed, spectrum. *Bottom left*: ^{12}CO absorption spectrum with expanded velocity scale. *Top right*: Observed ^{13}CO spectrum with model fit. *Middle right*: ^{13}CO absorption spectrum obtained by subtracting fitted emission line from observed spectrum. *Bottom right*: ^{13}CO absorption spectrum with expanded velocity scale. All temperatures are given as 0.62 T_{mb}

We have also combined the near-infrared photometry summarized by Grasdalen and Joyce (1976; their Table 2) with the model nuclear spectrum by Grindlay (1975) to obtain a value $A_V = 27$ mag. Giles (1986) estimates an extinction $A_V = 25 \pm 8$ mag towards the 2.2 μm source he identifies with the nucleus.

This source is offset by several arcsec from the optical 'nucleus' which has approximately $A_V = 2$ mag. Hardning et al. (1981) find extinctions in the range $A_V = 3 - 6$ mag at various positions in the dark band crossing NGC 5128. This suggests that (a) the dark band is characterized by relatively modest extinction on

average and (b) that the nucleus is obscured by a relatively small, but very dense circumnuclear cloud, in agreement with the far-infrared result of Joy et al. (1988).

On the basis of the above, we adopt $A_V = 27 \pm 5$ mag for the extinction of the nucleus of NGC 5128, which is the mean extinction on a scale of a few arcsec (24 pc arcsec^{-1}). This extinction corresponds to a column density to the nucleus $N_H = 5 \pm 1 \, 10^{22}$ cm^{-2} (Bohlin et al., 1978). This value is in excellent agreement with column densities estimated from X-ray observations (cf. Mushotzky et al., 1978, and references therein). We also note that Cunningham et al. (1984) deduced a column density through all of NGC 5128 $N_H = 3 \, 10^{22}$ cm^{-2}, from 400 μm observations in an 80″ beam. If about ten per cent of their beam is filled by the circumnuclear cloud, their result is in good agreement with the dark band extinction values of Harding et al. (1981).

Summarizing the above, we conclude that NGC 5128 possesses a circumnuclear cloud of size not much less than 400 pc (Joy et al., 1988; Giles 1986; Mushotzky et al., 1978) with a mass of order $2 \, 10^7 \, M_\odot$ and a central column density throughout of order 10^{23} H cm^{-2}. For dynamical reasons, and because of the existence of well-collimated radio jet structures in the core of Centaurus A (cf. Van der Hulst et al., 1983; Meier et al., 1988) we expect the circumnuclear cloud to have the shape of a torus or disk with a central cavity. Note that such a structure would not be unique to Centaurus A: similar rotating circumnuclear disks have been observed in galaxies such as M 82 and NGC 3079 (Lo et al., 1987; Sofue et al., 1987; Young et al., 1988).

3.2. Molecular hydrogen in the core of Centaurus A

3.2.1. Excitation

The unresolved nature of the detected H$_2$ emission ($\leq 4'' = 97$ pc FWHM) supports the above conclusion, and suggests that the emission arises from excited H$_2$ coating the inner edge of the circumnuclear disk. Table 3 summarizes the observed line ratios as well as those expected for radiative (nonthermal) excitation, and thermal excitation at temperatures of 1000 and 2000 K (Black and Van Dishoeck, 1987). At first glance, the observed $1-0 \, S(1)/2-1 \, S(1)$ ratio favors thermal excitation, although a small fluorescent contribution cannot be excluded. However, model calculations by Sternberg and Dalgarno (1989) show that

at high densities ($n_H > 10^5$ cm^{-3}) and strong UV radiation fields ($I_{UV} > 100$), the lower transitions of radiatively excited H$_2$ are collisionally deexcited, leading to line ratios that cannot be distinguished from shock-excited line ratios. Here I_{UV} denotes the enhancement of the UV radiation field over the average Galactic interstellar value. For very high $I_{UV} > 10^5$, the gas is heated to such high temperatures that collisional excitation in UV-heated gas may play a role as well. The current data cannot distinguish between these possibilities, and observations of higher H$_2$ transitions are needed to determine the excitation mechanism. The model of the Centaurus A nucleus by Grindlay (1975) predicts that the continuum radiation corresponds to $I_{UV} > 10^5$ within about 3.5 pc from the nucleus. The analysis in section 3.5 appears to rule out the presence of molecular material very close (< 40 pc) to the nucleus. In the following we assume that the observed H$_2$ is mostly collisionally excited. The ratios and upper limits in Table 3 then indicate H$_2$ excitation temperatures 1000 K $< T <$ 2000 K. In particular the limit on the $1-S(1)/S(2)$ ratio suggests an excitation temperature near the low end of this range.

3.2.2. Luminosity

The intrinsic ratio $1-0 \, S(1)/Q(3) = 1.42$ does not depend on the excitation mechanism as these lines arise out of the same upper state; they can be used to estimate the extinction (cf. Scoville et al., 1982). We observe $1-0 \, S(1)/Q(3) = 1.2 \, (+0.7, -0.4)$, which implies a formal extinction value $A_{2.1} = 0.95 \, (+2.2, -0.95)$ mag, or $A_V \leq 26$ mag. This estimate is consistent with the extinction of the nucleus derived in Sect. 3.1, especially if the circumnuclear disk is slightly tilted. Consequently, the extinction-corrected strength of the $1-0 \, S(1)$ line is $1.0 \, (+6.0, -0.5) \, 10^{-13}$ erg s^{-1} cm^{-2}, and the corresponding surface brightness $\sigma(10-S(1)) \geq 1.2 \, 10^{-4}$ erg cm^{-2} s^{-1} sr^{-1}. If the H$_2$ is shock-excited, model calculations by Shull and Hollenbach (1978) show that such a surface brightness indicates high densities $n_H \geq 10^4$ cm^{-3}, as well as shock velocities $v \geq 10$ km s^{-1}. These same models show the total intensity of all H$_2$ lines to be about 15 times the intensity of the $1-0 \, S(1)$ lines. Thus, the total H$_2$ luminosity of the Centaurus A nucleus is $1.0 \, (+7.0, -0.5) \, 10^6 \, L_\odot$. Since the far-infrared luminosity of the nuclear cloud is $1.5 \, 10^9 \, L_\odot$, we find $L(H_2)/L(\text{tot}) = 0.75 \, (+4.5,$

Table 3. H$_2$ line ratios

Transitions	Fluorescence[a]	Shock[a]		Centaurus A
		$T = 1000$ K	$T = 2000$ K	observed
$1-0 \, S(1)/1-0 \, S(0)$	2.2	3.7	4.7	2.1 (+2, −1)
$1-0 \, S(1)/1-0 \, S(2)$	2.0	3.7	2.7	≥ 4.2
$1-0 \, S(1)/2-1 \, S(1)$	1.8	200	12.1	≥ 3.4
$1-0 \, S(1)/1-0 \, Q(1)$	1.0	0.96	1.43	1.2 (+0.7, −0.4)
$1-0 \, S(1)/1-0 \, Q(3)$	1.42	1.42	1.42	1.2 (+0.7, −0.4)
$1-0 \, S(1)/1-0 \, Q(4)$	3.6	6.6	4.8	≥ 4.2

[a] From Black and Van Dishoeck (1987)

$-0.5) 10^{-3}$. This is similar to values found for much smaller Local Group H II regions (Israel and Koornneef, 1988; Israel et al., 1989). Note that if the H_2 were radiatively excited, the luminosity would be an order of magnitude larger. In that case, high densities $n_H > 10^4$ cm^{-3} would be required as well to explain the observed H_2 surface brightness.

The parameters of the H_2 emitting region are further constrained by the absence of detectable Brackett-γ emission. The upper limit on the flux is $1.2\,10^{-14}$ erg s^{-1} cm^{-2}, or about $2\,10^{-13}$ erg s^{-1} cm^{-2} if the maximum possible extinction derived from the H_2 line ratios is adopted. For comparison, the upper limit on the reddening-corrected Br-α flux is $1.8\,10^{-12}$ erg s^{-1} cm^{-2} (Grasdalen and Joyce, 1976). The measured upper limit to the (uncorrected) (Br-γ is an order of magnitude larger than that predicted from the ionizing flux distribution as specified by Grindlay (1975). Thus, we can use Eqs. (25) and (29) of Black and Van Dishoeck (1987) to put limits on the number of early type stars in the H_2 emitting zone, and on the resulting average UV radiation field. We obtain $I_{UV} < 50$, or $I_{UV} < 750$ if the maximum reddening correction is applied. This corresponds to upper limits on the number of early type stars with a mean Lyman continuum photon flux of $5\,10^{48}$ s^{-1} of $N_* < 2.4\,10^3$, or $N_* < 4\,10^4$ for maximum reddening.

3.3. CO emission towards the nucleus

3.3.1. Profile parameters

Our $J = 1-0$ ^{12}CO result on the center of NGC 5128 agrees well with that obtained in the $J = 2-1$ line by Phillips et al. (1987, 1988) in a 30″ beam. They find $T_{mb} = 330 \pm 20$ mK (cf. Phillips et al., 1988; their Fig. 3), yielding a ratio $T_{mb}(2-1)/T_{mb}(1-0) = 0.75 \pm 0.05$. Both our observations and those by Phillips et al. (1987) show that CO emission strengths change little going away from the nucleus, so that this result is largely independent of resolution (30″ vs 40″). As both the SEST and CSO dish surfaces are quite good, we assume that at the observing frequencies the potentially troublesome effect of the error patterns can be neglected. The nominal temperature ratio then indicates an excitation temperature $T_{ex} = 8 \pm 2$ K. However, within the uncertainties introduced by the calibration, the temperature ratio is not significantly different from that expected for $T_{ex} = 10$ K, usually assumed for ensembles of molecular clouds. The $J = 1-0$ profile is broader than the $J = 2-1$ profile (FWHM 140 km s^{-1} vs. 105 km s^{-1}), but this is fully explained by our somewhat larger observing beam and the steep rotation curve of the inner regions of NGC 5128 (160 km s^{-1} arcmin^{-1}, see Van Gorkom, 1987; Phillips et al., 1988).

Optical determinations of the systemic velocity are in the range $V_{Hel} = 536$–548 km s^{-1} (Bland, 1985; Wilkinson et al., 1986; Graham, 1979), but do not sample the nucleus itself (Giles, 1986). From our central CO profile we find $V_{Hel} = 548 \pm 4$ km s^{-1}, in perfect agreement with $V_{Hel} = 547 \pm 5$ km s^{-1} as found by Phillips et al. (1987). However, because of the steep velocity gradient in the central region, this value is rather susceptible to small pointing errors. Note that for $V_{Hel} = 550$ km s^{-1}, the peak absorption is virtually at the assumed systemic velocity.

3.3.2. Excitation temperature and mass

We observe a ratio $T_{mb}(^{12}CO)/T_{mb}(^{13}CO) = 12 \pm 1$ over most of the profile, so that the mean ^{13}CO optical depth is 0.09 ± 0.02

assuming LTE conditions. The nominal excitation temperature $T_{ex}(^{12}CO) = 8 \pm 2$ K implies a beam dilution factor of 11 ± 4; taking $T_{ex} = 10$ K yields a beam dilution factor of 15. This partly reflects the observed patchy nature of the dark band, but probably also small-scale clumping.

For an assumed ratio $N(H_2) = 5\,10^5 \, N(^{13}CO)$ (Dickman, 1978) our $^{12}CO/^{13}CO$ observations yield a column density $N(H_2) = 6\,10^{21}$ cm^{-2} (hence $N_H = 1.2\,10^{22}$ cm^{-2}), corresponding to a mass $M(H_2) = 7\,10^7 \, M_\odot$ in the 40″ beam. To this should be added a contribution by H I, which is of order $N_H = 0.5\,10^{22}$ cm^{-2} for a spin temperature $T_s = 100$ K (see Van der Hulst et al., 1983). This column density should be compared to $N_H = 3\,10^{22}$ cm^{-2} found by Cunningham et al. (1984) at 400 μm in an 80″ beam. The two values differ by a factor of two only, which is good agreement considering the uncertainties involved. Taking the integrated ^{12}CO signal $I_{CO} = 62$ K km s^{-1}, and the Galactic CO/H_2 conversion factor from Bloemen et al. (1986), we obtain $N(H_2) = 1.4\,10^{22}$ cm^{-2} ($N_H = 2.8\,10^{22}$ cm^{-2}), or $M(H_2) = 1.6\,10^8 \, M_\odot$. We conclude that the central total hydrogen column density of NGC 5128 is of order $N_H = (2 \pm 1)\,10^{22}$ cm^{-2}, corresponding to a total extinction through all of NGC 5128 of $A_V = (11 \pm 5)$ mag. The mass in the beam is then $M_H = (1.2 \pm 0.6)\,10^8 \, M_\odot$. Since this represents all mass in a column with radius $r = 485$ and depth equal to the galaxy diameter, comparison with the mass of the circumnuclear material $M_H = 2\,10^7 \, M_\odot$ (Sect. 3.1) shows that most of the CO emission arises in the dust band, probably at considerable distance from the nucleus. The values derived above for N_H and A_V (representing the average over a 40″ beam) therefore apply primarily to the dark band material and not to the circumnuclear cloud which has a small filling factor (≤ 0.05). The CO results thus confirm the conclusions of Sect. 3.1.

Far-infrared [C II] emission at 158 μm has been observed towards the center of NGC 5128 with a 60″ beam (Crawford et al., 1985). Comparison of [C II] and integrated $J = 1-0$ CO line intensities places the NGC 5128 source on the empirical relation found by Crawford et al. (1985) for a variety of Galactic and (active) extragalactic sources. The far-infrared line to continuum ratio is also rather similar to those presented by Crawford et al. for the nuclei of IC 342 and M 51. However, since the origin of Cen A [C II] emission (center or dark band) is not known, the implications of this similarity are not clear at present.

3.4. CO absorption toward the nucleus

3.4.1. Optical depth and excitation temperature

Towards the nucleus, deep and narrow absorption features are seen. Several arguments show conclusively that this is absorption against the nucleus, and *not* self-absorption. First, the lines are very narrow whereas self-absorbed lines should be much broader. Second, the absorption is of similar depth in the $J = 1-0$ and $J = 2-1$ ^{12}CO transitions; it is also quite deep in the $J = 1-0$ ^{13}CO profile (in fact, for ^{13}CO $T_{mb}(abs)/T_{mb}(em) = 1.8 \pm 0.3$). Third, offset from the nucleus, CO emission shifts away from the same velocity: the absorption does not follow the emission. Moreover, moving the beam off the nucleus, the absorption depth decreases with the apparent continuum strength of the unresolved core, while CO emission strengths remain the same. Thus, there is no doubt that the absorption takes place against the nucleus only. Note also that the H I (Van der Hulst et al.,

1983) and H$_2$CO absorptions (Gardner and Whiteoak, 1976a,b) clearly occur against the nucleus and inner jets. Since the compact core is the only source of radiation in the millimeter continuum, the *absorption* takes place in a pencil beam with diameter of about 0.01 pc (2500 AU) as opposed to the *emission* which arises from a column of diameter 960 pc. Thus, the observed emission and absorption are virtually *independent*. Figure 3 shows the ^{12}CO and ^{13}CO absorption spectra, obtained by subtracting model fits to the emission from the observed profiles. The deepest absorption line is at $V_{Hel} = 550 \pm 3$ km s^{-1}, i.e. within the errors at the systematic velocity. Its intrinsic width is about 6.5 km s^{-1} and its depth $T_{mb} = -0.28 \pm 0.02$ K. In the same spectrum, the continuum from the compact nucleus has a strength of 0.38 K, so that the implied optical depth is $\tau_{abs}(^{12}\text{CO}) = 1.4 \pm 0.2$. *The ratio of CO absorption depth to continuum emission strength is independent of the calibration, and independent of the absolute pointing*, as both vary in tandem. Nevertheless, the derived optical depth is only a *lower limit*, as it assumes (a) that the absorption is completely resolved in velocity, (b) that the obscuring material covers the continuum core completely and (c) that CO emission associated with the absorbing material is negligible. The corresponding feature in the ^{13}CO profile has $T_{mb} = -0.064 \pm 0.008$ K, i.e. an optical depth $\tau_{abs}(^{13}\text{CO}) = 0.22 \pm 0.03$. In contrast to $\tau_{abs}(^{12}\text{CO})$, this value should be fairly accurate: a 50% increase in absorption depth would only yield $\tau_{abs}(^{13}\text{CO}) = 0.36$. The blueshifted absorption blend has a nominal optical depth $\tau_{abs}(^{12}\text{CO}) = 0.48 \pm 0.07$. Again this is strictly a lower limit.

By using the extinction data summarized in Sect. 3.1, we may obtain a rough estimate of the excitation temperature pertaining to the absorbing material. The central few arcsec of the nucleus of NGC 5128 suffer an extinction of 27 ± 5 mag, of which up to 6 mag could be due to the dark band. Whether the dark band contributes at all is uncertain in view of the relatively small filling factor derived from the CO emission measurements. Thus, the compact core should also suffer an extinction of about $A_V = 27$ mag, unless it is located behind a gap in the obscuring material. Since the disk of NGC 5128 is nearly edge-on, the opposite (even higher extinction) is in fact more likely. As the total ^{13}CO absorption is about $\int \tau \, dV = 1.6$ neper K km s^{-1}, its column density will be $N(^{13}\text{CO}) = 3.7 \, 10^{14} f(T_{ex})$; $f(T_{ex}) = (T_{ex} + 0.9)/(1 - \exp[-5.3/T_{ex}])$. From Dickman (1978) and Bohlin et al. (1978) we obtain $A_V/N(^{13}\text{CO}) = 5 \, 10^{-16}$ cm^2 mag, so that $A_V = 0.2 f(T_{ex})$, within a factor of two or so. For $T_{ex} = 10$ K, the extinction caused by the obscuring material would therefore be only $A_V = 5$ mag, which is unacceptably low. However, for $T_{ex} = 25 \pm 7$ K the implied ^{13}CO column density would indeed predict the correct A_V; the error in T_{ex} represents a formal uncertainty of 50% in the conversion. Thus, the absorbing molecular material would be at an elevated excitation temperature, as could be expected from material close to the luminous nucleus (cf. $T_{ex} = 25$–40 K found for the nucleus of IC 342 by Ho et al., 1987 and Eckart et al., 1989). This result depends, of course, on the applicability of Galactic abundances.

3.4.2. Comparison with other absorption features

The ^{12}CO absorption spectrum is complex. Next to the main feature at $V_{Hel} = 550$ km s^{-1} we find a second feature which has the appearance of a blend of lines at $V_{Hel} = 538$ and 543 km s^{-1} of depth $T_{mb} = -0.145 \pm 0.015$ K, hence $\tau_{abs}(^{12}\text{CO}) > 0.5 \pm 0.1$. In fact, weak absorption $T_{mb} \leq 0.025$ K may be present at V_{Hel}

$= 530$ km s^{-1} as well. Here, we note that the overall appearance of the ^{12}CO absorption profile is similar to that of the C$_3$H$_2$ and H$_2$CO absorption profiles (Bell and Seaquist, 1988; Gardner and Whiteoak, 1976a,b).

On the blue side of the main component, the C$_3$H$_2$ and H$_2$CO spectra show secondary features at $\Delta V = V - V_{main} = -6$ and -11 km s^{-1} corresponding to the CO absorption blend. The H I spectrum shows significant absorption at the same velocities (Gardner and Whiteoak, 1976a), but mostly against the inner jet, and not the nucleus, and probably caused by material at considerable distance from the nucleus. Against the nucleus, only the $\Delta V = -12$ km s^{-1} feature is weakly seen in absorption (optical depth (H I ≈ 0.1; see Van der Hulst et al., 1983). Thus, we find for this cloud $\tau(^{13}\text{CO})/\tau(\text{H I}) = 0.7 \pm 0.3$, while the main peak has $\tau(^{13}\text{CO})/\tau(\text{H I}) = 0.17 \pm 0.02$. Although subject to considerable uncertainty, the comparison indicates that these absorption features are due to clouds with a high molecular content. This is also illustrated as follows. For Galactic abundances and H I spin temperatures $T_s = 100$ K, the VLA measurements of H I components in front of the nucleus correspond to $A_V \approx 3$ mag, leaving of order $A_V \approx 24$ mag for molecular gas, thereby implying a ratio $N(\text{H}_2)/N(\text{H I}) \approx 4$.

On the red side, the C$_3$H$_2$ profile shows uncertain, weak absorption in the range of $\Delta V = (+19)$–$(+74)$ km s^{-1}. The H$_2$CO profile shows equally uncertain, weak absorption in the range $\Delta V = (+9)$–$(+34)$ km s^{-1}. A generous upper limit to any ^{12}CO absorption at these velocities is $\tau_{abs}(^{12}\text{CO}) < 0.5$. In contrast, the VLA observations clearly show redshifted H I absorption components against the nucleus at $\Delta V = +23$ and $+42$ km s^{-1} (Van der Hulst et al., 1983). From $\tau(^{12}\text{CO}) \leq 0.5$, we estimate ratios $\tau(^{13}\text{CO})/\tau(\text{H I}) \leq 0.05$. Thus, the redshifted clouds are poor in molecular material. From their C$_3$H$_2$ observations, Seaquist and Bell (1986) reached a similar conclusion (see also Gardner and Whiteoak, 1976a,b).

All spectra show several clouds in absorption against the nucleus. If we assume the main absorption peak to be at the systemic velocity, the other clouds deviate in velocity by as much as -15 to $+45$ km s^{-1}. Individual clouds have only small velocity dispersions (a few km s^{-1}, see also Gardner and Whiteoak, 1976a; Bell and Seaquist, 1988). We have seen that the blueshifted clouds (i.e. those moving away from the nucleus) are relatively rich in molecular material as is the cloud at the systemic velocity. In contrast, the redshifted clouds (moving towards the nucleus) have a low molecular content. Van der Hulst et al. (1983) have suggested that these clouds are falling into the nucleus as part of an accretion process fueling the nucleus. The absence of blueshifted H I clouds in a sample of galaxies (including NGC 5128) is also used as evidence for infall by Van Gorkom et al. (1989). The presence of *blueshifted* molecular clouds with significant deviations from systemic velocity weakens this argument. An alternative would be clumps of material in elliptical orbits around the nucleus with a large velocity dispersion (of order 60 km s^{-1}) but in that case, the striking difference in molecular content between the redshifted clouds and the other clouds does not have an immediate explanation.

3.5. Constraints on the properties of a circumnuclear disk

The masses and column densities derived in Sects. 3.1–3.4 imply an effective area covered by the cloud $M_H/N_H = 4 \pm 2 \, 10^4$ pc^2 which is *independent* of the assumed gas-to-dust ratio. The

outer radius of the cloud should be about 200 pc or somewhat smaller, while our H_2 observations require densities of order 10^3–10^4 H cm^{-3} at an inner edge at a radius of about 50 pc or less. *The need to satisfy a relatively high mass, a relatively low line-of-sight column density as well as the above size and density requirements severely constrains possible configurations and density distributions.* For instance, a homogeneous sphere would have a radius of 95 pc and a density of only $n_H = 170$ cm^{-3}, both values too small to fit our requirements. A flattened sphere would have a larger outer radius, but a lower density. Homogeneous shells and disks have much the same problem: they cannot be fitted to both the size and density required. Structures with small volume filling factors (e.g. small, dense clumps; mini-spiral arms) make matters worse. In fact, only relatively thick disks with density gradients yield possible solutions. These may be further constrained by requiring cavity size to be comparable to disk thickness. For example, a 'fat' disk with a diameter of order 325 pc (13″), a thickness of about 80 pc (3″.5) and a central cavity also of size 80 pc, an inner edge density $n_H = 2\ 10^4$ cm^{-3}, and a physically plausible density gradient $n(r) \sim r^{-2}$ satisfies all requirements imposed by the available observational material. Although this solution is not uniqe, it serves to illustrate typical characteristics of the circumnuclear cloud; we emphasize that significantly different geometries do not yield acceptable solutions unless one of the observational constraints is grossly in error. Our analysis also suggests that a relatively modest improvement in resolution over that of the (infrared and millimeter) observations presented in this paper should be sufficient to spatially resolve the circumnuclear disk and thereby verify our conclusions.

4. Conclusions

We have observed ^{12}CO and ^{13}CO emission and absorption towards the nucleus of NGC 5128 (Centaurus A), as well as an unresolved source of excited H_2 emission (size < 95 pc). Analysis of published observations shows that the nucleus of Cen A is surrounded by a compact (size < 400 pc), dense and warm dust cloud. Optical and infrared measurements indicate a rather high extinction $A_V = 27 \pm 5$ mag towards the nucleus, and more modest extinctions corresponding to the dark band silhouetted against the galaxy. The circumnuclear cloud should have the shape of a thick disk with a central cavity. Its mass is of order $2\ 10^7\ M_\odot$. Most likely, the observed excited H_2 is coating the inner edge of the disk. The CO emission appears to arise mostly from the dark band; it is characterized by excitation temperatures of order 10 K, and a surface filling factor of order 0.1. The narrow CO absorption features are seen against the nucleus; self-absorption is ruled out. If the compact radio continuum core, seen in the 110/115 GHz CO measurements, suffers the same extinction as the nucleus as a whole, the excitation temperature of the absorbing material is of order $T_{ex} = 25 \pm 7$ K. Redshifted H I clouds, often interpreted as material falling towards the nucleus, are poor in molecular material as compared to clouds at the systemic and blue-shifted velocities.

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