# Molecular Absorption in Centaurus A: Probing a Circumnuclear Disk

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When the Swedish-ESO Submillimetre Telescope (SEST) became available, many observers jumped at the opportunity to study molecules, especially CO, in hitherto inaccessible southern galaxies. So did we: our group has started a molecular survey of all southern galaxy nuclei detected with IRAS at 12 micron. We suspected that these galaxies would contain significant molecular concentrations in their central regions. Our survey intended to establish this and to derive basic properties of central molecular clouds for a large sample of galaxies.

## Cen A Molecular Absorption: a Unique Case

Among the first series of objects observed was the nucleus of NGC 5128, parent galaxy of the strong radio source Centaurus A. We were quite surprised to discover, in the low-resolution back-end of the SEST, a clear and narrow absorption feature in the broad CO J=1−0 emission from the centre of this galaxy. This was unexpected, as just-published CO J=2−1 observations made with the CalTech Submillimetre Observatory (CSO) in Hawaii had failed to show absorption lines. Later, it was discovered that they are in fact present in unsmoothed data. The published CSO data were smoothed in order to increase the signal-to-noise ratio, and the narrow absorption was inadvertently filled in. At the time of our observation, the centres of several galaxies (including Centaurus A) were known as sources of molecular line absorption, but only at centimetre and decimetre wavelengths. Even now, *Centaurus A is the only extragalactic source in the sky with known (sub) millimetre absorption lines*. The reason is, of course, that we need a sufficiently strong continuum background source against which we can see the absorption. Most galaxies have nonthermal radio nuclei with only very weak emission at high frequencies. Only a very compact nucleus, as found in Cen A foots the bill. At wavelengths above a few centimetres, the radio nucleus of Cen A is resolved by VLBI measurements into a central radio source and inner jets, but their continuum emission is negligible at mm wavelengths. There, however, emission from the compact nucleus itself (optically thick above a few centimetres) has become strong. The VLBI observations show this nucleus to have a size of 0.5 milliarcsec (corresponding to about 0.01 pc or 2500 A.U. for a distance of 5 Mpc), i.e. much smaller than the SEST beam (40 arcsec at 115 GHz). Not only is Cen A unique in the sky, it is also well placed for observations with the SEST, as it passes high overhead at La Silla.

## The Circumnuclear Disk Inferred

We also included NGC 5128 in our ESO 3.6-m/IRSPEC survey of southern galaxy nuclei for $H_2$ emission. Observations of the 1-OS (1) transition showed that the $H_2$ source in the nucleus should have a diameter of about 4 arcsec (corresponding to 95 pc). Data in the literature show that the nucleus of NGC 5128 is heavily obscured, with $A_V$ = 15−25 mag. This extinction drops rapidly when going away from the nucleus. Moreover, far-IR observations with the Kuiper Airborne Observatory have shown that there exists in the centre of the galaxy a dense, warm ($T_d$ = 35−45 K) dust cloud with a diameter less than 16 arcsec (385 pc). The combination of extinction and far-IR emission led us (Paper I) to propose the existence of a circumnuclear disk in Cen A with an overall diameter of about 400 pc, a mass of

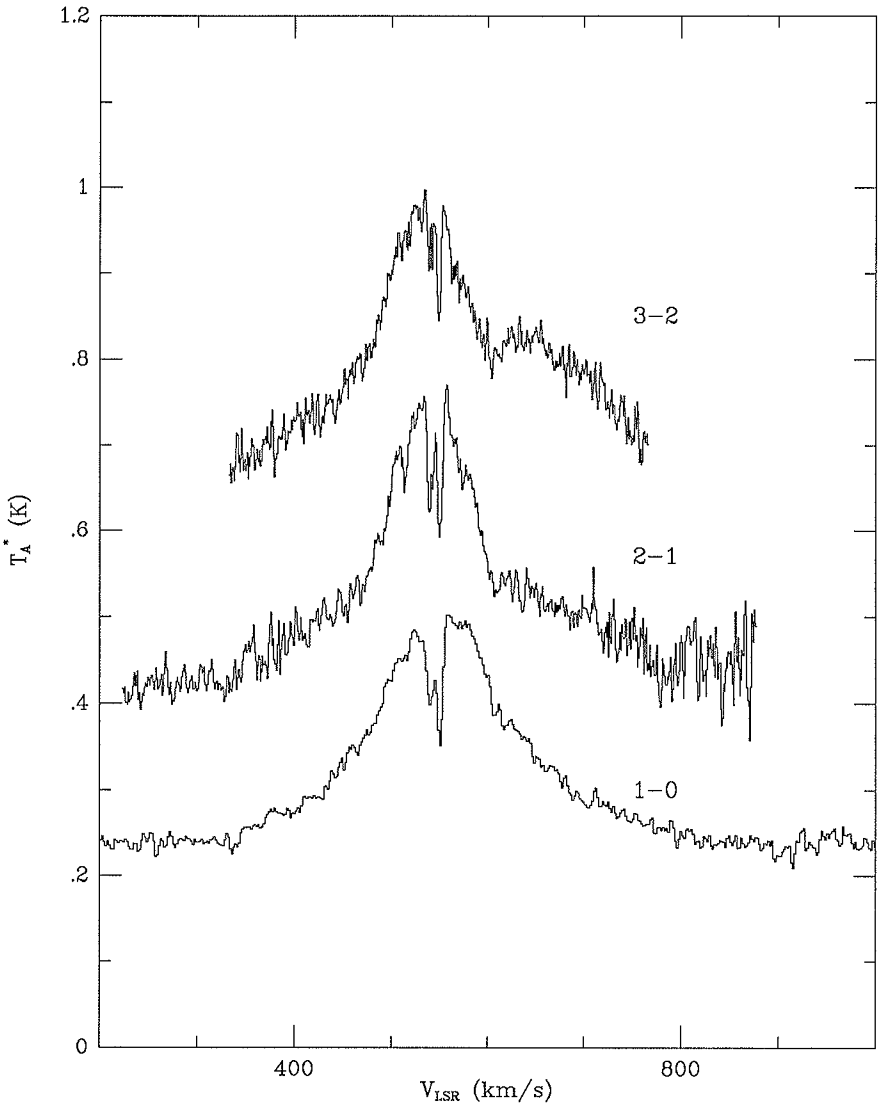


Figure 1: *$^{12}$CO J=1−0, 2−1 (SEST) and 3−2 (CSO) spectra of the Cen A nucleus, smoothed to resolutions of 2.8, 0.9 and 0.9 km/s respectively. The 2−1 and 3−2 spectra have been offset by 0.25 K and 0.45 K respectively.*

* The work described in this paper was carried out in close collaboration with F. Baas, E.F. van Dishoeck (both Leiden), J. Koornneef (STScI), Th. de Graauw (Groningen), and also involved J.H. Black (Arizona) and T.G. Phillips (CalTech).

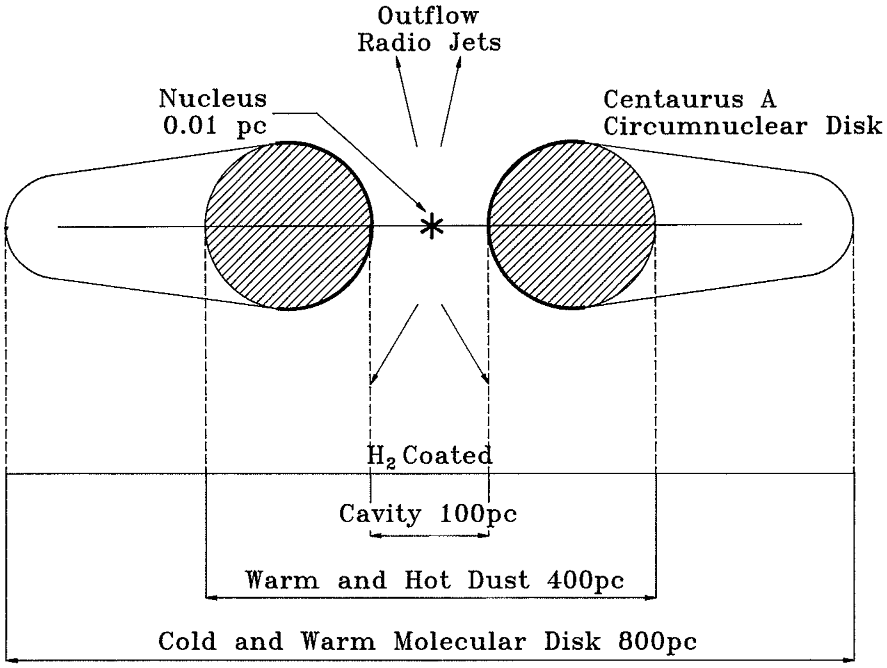


Figure 2: *Schematic representation of the Cen A circumnuclear disk seen edge-on (not to confuse with the NGC 5128 dark band).*

order $2 \times 10^7$ $M_\odot$, and a density gradient of order $n(r) \propto r^{-2}$. It should contain a central cavity of diameter 90 pc, whose edge is coated with $H_2$ excited by radiation and winds from the nucleus. *This circumnuclear disk should not be confused with the optically visible dark band crossing NGC 5128.* This dark band is located in the disk of the galaxy at much larger distances to the nucleus.

## The Circumnuclear Disk Resolved

No unique solution could be derived from observations that do not spatially resolve this disk, but the literature data in particular put strong constraints on permissible configurations. The sizes inferred for the disk and the cavity suggested that only small increases in resolution at both mm and IR wavelengths would suffice to spatially resolve it. In the near-IR, arcsec-resolution observations should resolve the cavity. In the millimetre range, use of the SEST in the CO J=2−1 transition (20 arcsec resolution) should show the signature of the circumnuclear disk. Our SEST observations at 230 GHz indeed confirm this (Figure 1; Paper II). The CO J=2−1 data show the relatively strong continuum of Cen A, as well as the CO emission profile due to molecular gas in the outlying dark band. The profile width is primarily determined by the galactic rotation of the material in the 20 arcsec beam. Indeed, the CO J=1−0 emission profile (40 arcsec resolution) is significantly broader, as it covers a larger segment of the steep rotation curve of NGC 5128. However, *the CO J=2−1 measurement also shows a broad, plateau-like component underlying the regular emission profile.* A CSO measurement of the CO J=3−2 profile with 20 arcsec resolution also suggests the presence of this plateau. The plateau has a velocity half-width of 260 km/s, indicating the presence of rapidly rotating material, hence material close to the nucleus, within the beam. Comparison of SEST and CSO CO measurements with different beam-sizes imply that the size of the plateau-emitting region is 35 arcsec (820 pc). Clearly, *we have found the signature of the circumnuclear disk that so far was only inferred.* Its size is about twice that estimated from the emission of warm dust. Thus, the circumnuclear disk not only has a density gradient, but also quite plausibly a temperature gradient. As the CO emission profile samples relatively cool material as well as hotter material, it indeed should show a greater extent than the very temperature-dependent far-infrared emission. Figure 2 shows a schematic representation of the circumnuclear disk seen edge-on, as from Earth.

## The Absorption Line Survey

As soon as we saw the narrowness of the absorption features, we realized the importance of using the high-resolution SEST back-end in parallel with the low-resolution back-end (when not broken!) in order to obtain high signal-to-noise measurements of not only the CO absorption lines, but also absorption lines of other molecular species such as $HCO^+$, CN, $C_3H_2$, $C_2H$, HCN, HNC, etc. Both back-ends are needed: high resolution to show the absorption lines in their full glory, low resolution to show the continuum level in the presence of emission. Whereas the emission is due to material spread over the full area covered by the beam, the absorption samples only a 0.01 pc pencil beam towards the nucleus. With that pencil beam, we observe only a narrow column through any cloud or cloudlet that is in the line of sight to the nucleus. The beauty of these measurements is that the simultaneous measuring of absorption depth and background continuum strength at one stroke eliminates all disturbing effects due to beam-source coupling and pointing errors and leads directly to *optical depths completely independent from these effects.*

## Main Absorption Lines

The absorption lines fall into three categories. In all molecular species detected by us the strongest absorption is near the systemic velocity of $V_{LSR}$ = 550 km/s. In $^{12}CO$ the absorption feature is completely saturated in all three transitions observed by us. It is most probably a blend of several much narrower individual components, all at about the systemic velocity. This greatly complicates the analysis, but we are reasonably certain that the majority of the absorbing material at these velocities is in the circumnuclear disk close to the nucleus and has excitation temperatures of 25 K (as compared to about 10 K for CO in the dark band). The columm density should be of order N(CO) = $10^{18}$ $cm^{-2}$. The second category consists of the strong absorption lines that are *blueshifted* with respect to the central feature. They consist of a narrow line (width about 1 km/s) at $\Delta V = -6$ km/s and a probable blend of lines at $\Delta V = -11$ km/s. Both have only weak HI counterparts. The CO column densities are half or less that of the central component. At present, it is uncertain whether they originate in clouds residing in the circumnuclear disk, or in clouds residing in the dark band.

## The Redshifted Absorption Line Forest: Probing the Monster Feasting

Most intriguing is the third category, a series of absorption lines, many apparently blended, at velocities *redshifted* up to $\Delta V = +65$ km/s or more. Almost certainly, they represent clouds falling into the nucleus (feeding the monster). The optical depth ratios of $HCO^+$ and CO vary strikingly for these lines. Also, they tend to have stronger HI counterparts than the blueshifted lines. This suggests that the infalling clouds suffer from enhanced cosmic-ray ionization rates, enhanced dissociation or shock-induced processes. The study of these very lines provides the exciting possibility of *finding out just how an active galaxy nucleus is fed by the surrounding galaxy.* As in most molecular species these absorption lines have optical depths of only a few tenths or less, very long integration times (4–8 hours per species) are needed with the present sensitivity of the SEST receivers in order to obtain a sufficiently high signal-to-noise ratio. We have now observed almost all molecular transitions in the 85 to 115 GHz range to the limits feasible at present (but wait till SEST gets a 115 GHz SIS receiver!).

### Future Observations

Still to be done are most transitions in the 230 GHz range. For this task, the new SIS receiver is essential. Even then it is not an easy task given the often non-optimal sky conditions at La Silla and the present pointing accuracy of the SEST. The planned installation of tiltmeters in the telescope, however, gives hope that the latter problem will be overcome soon. The observation of the 230 GHz window is of great importance, because it allows us to observe the higher transitions of the same species that were observed in the 100 GHz window. It is the comparison of different transitions of the same species, combined with interspecies comparison that has proven to be so fruitful in the past, and that we need here to unequivocally determine excitation temperatures, column densities and abundances.

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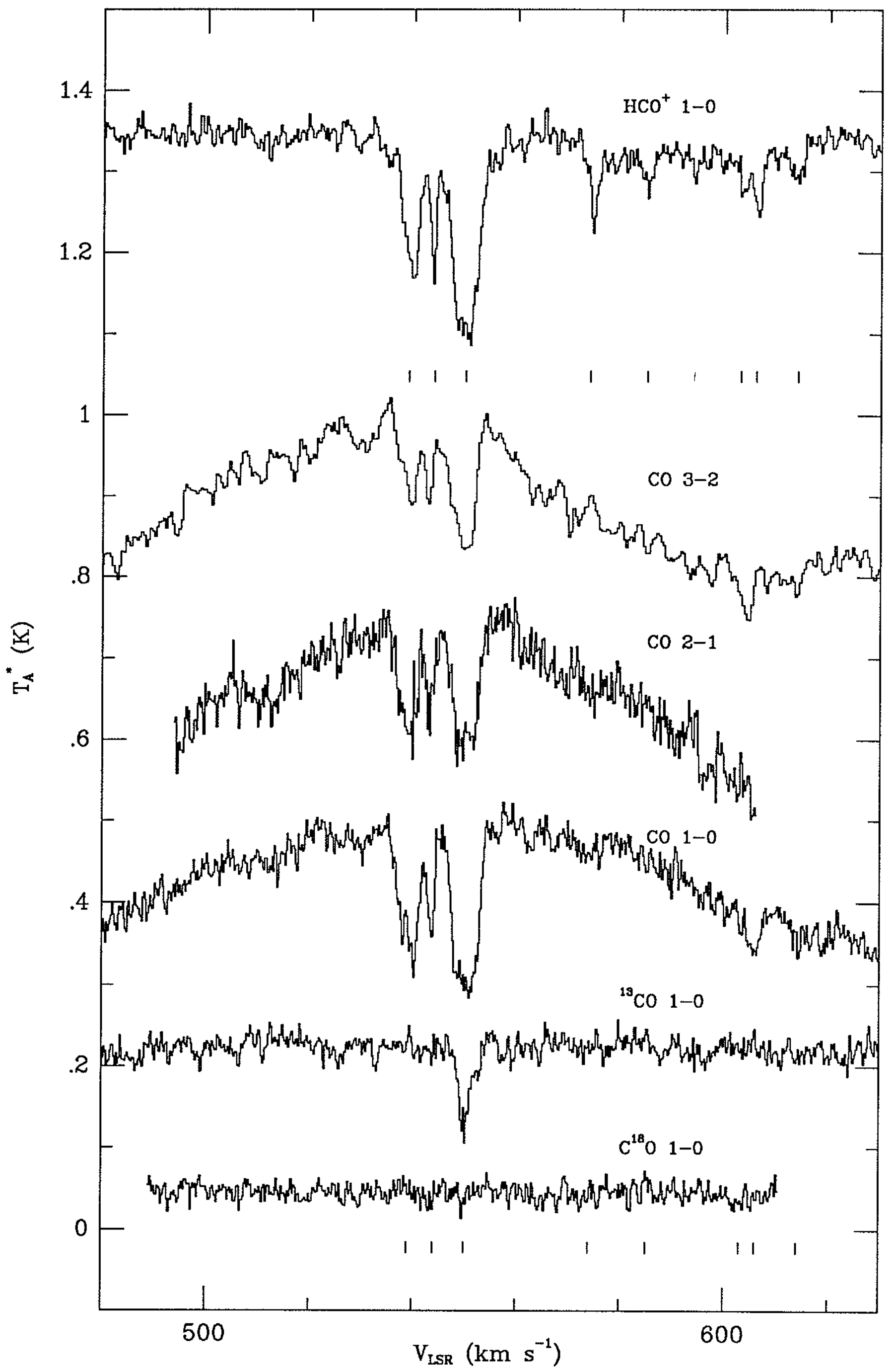


Figure 3: *High-resolution spectra of $HCO^+$ (1–0), CO (1–0), (2–1) and (3–2), as well as $^{13}CO$ (1–0) and $C^{18}O$ (1–0). The spectra have been shifted by +1.05, +0.4, +0.25, 0.0, –0.05 and –0.2 K respectively. Note the series of redshifted absorption components in the $HCO^+$ spectrum.*

# Microlensing in the "Cloverleaf" Quasar H1413+117?


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### 1. Introduction

The broad absorption-line quasar H1413 + 117 has been resolved in four components having comparable brightness by Magain et al. (1988). This makes the object a superb candidate for gravitational lens models. The angular separations of the images (noted A, B, C, D) are between 0.77″ and 0.96″. Individual spectra of the components were obtained at CFHT during a period of very good seeing (0.5″–0.6″) by Angonin et al. (1990). The four components have the same redshift (z = 2.55) and overall